Background evaluation at SuperKEKB and Belle II

Antonio Paladino on behalf of the Belle II background group - 2020/02/24

Novosibirsk - INSTR20 Conference

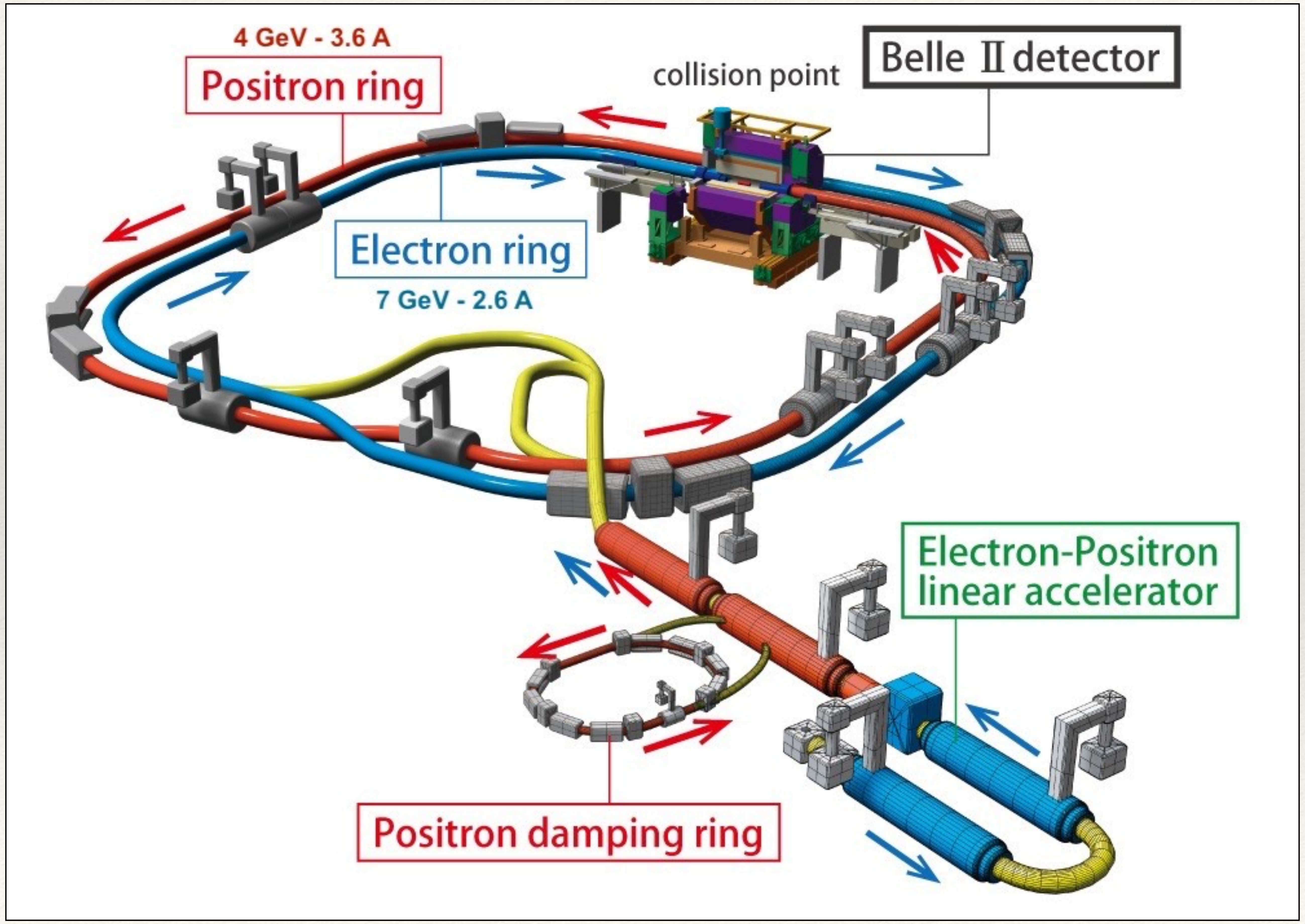
OUTLINE

- The SuperKEKB accelerator and the Belle II detector
- Summary of 2019 operations
- Background sources in SuperKEKB
- Background studies
  - Single beam background
  - Luminosity background
  - Synchrotron radiation
  - Injection background
- Prospects for 2020

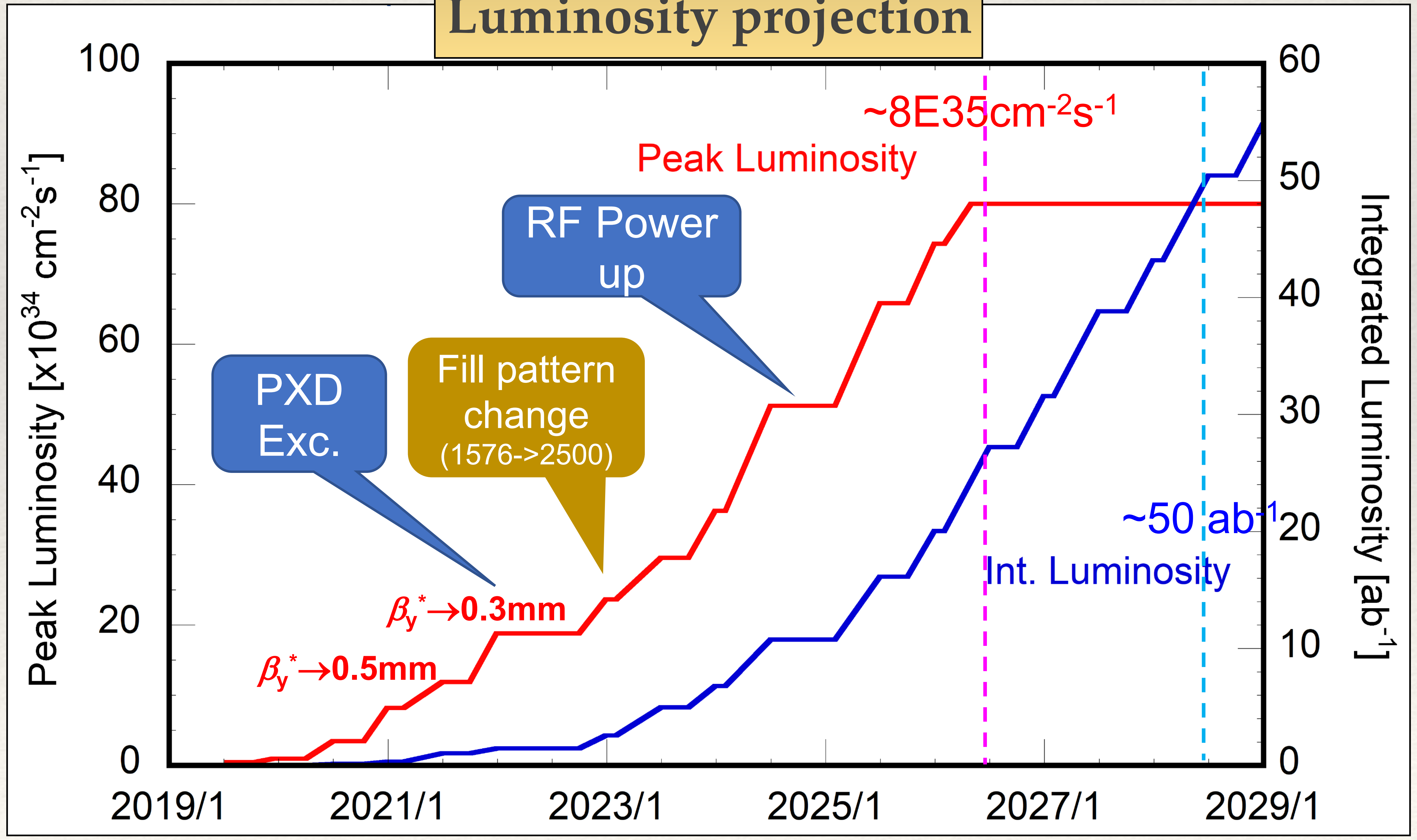
The SuperKEKB accelerator

- Asymmetric e^+e^- collider that aims to the unprecedented instantaneous luminosity of **8 x 10^{35} cm^{-2} s^{-1}**
- Upgrade of KEKB machine, **L_{inst} = 2.1 x 10^{34} cm^{-2} s^{-1}**
- **E_{CM}** = 10.58 GeV, Υ(4S)
- Belle II expected integrated luminosity of about **50 ab^{-1}**

SuperKEKB luminosity 40 times higher than KEKB:
- **Increase beam currents by factor 2.**
- **Nano-beam scheme:**
  - **Reduce by factor 20 vertical betatron function at IP.**



Luminosity projection

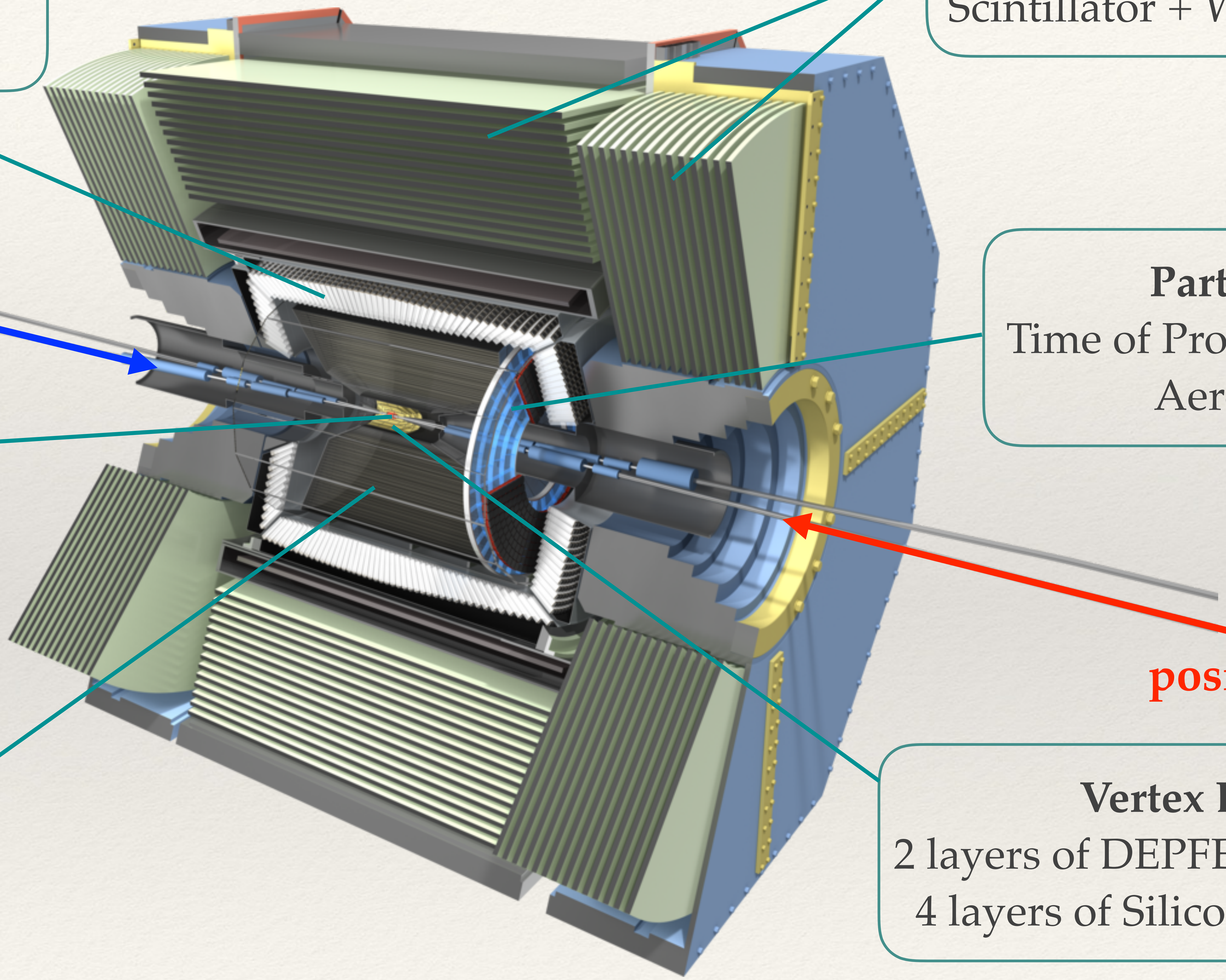


The Belle II detector

EM calorimeter
CsI (Tl) with waveform sampling electronics

KLM - K_L and muon detector
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

electrons - 7 GeV (HER)



Particle identification
Time of Propagation Counter (barrel)
Aerogel RICH (FWD)

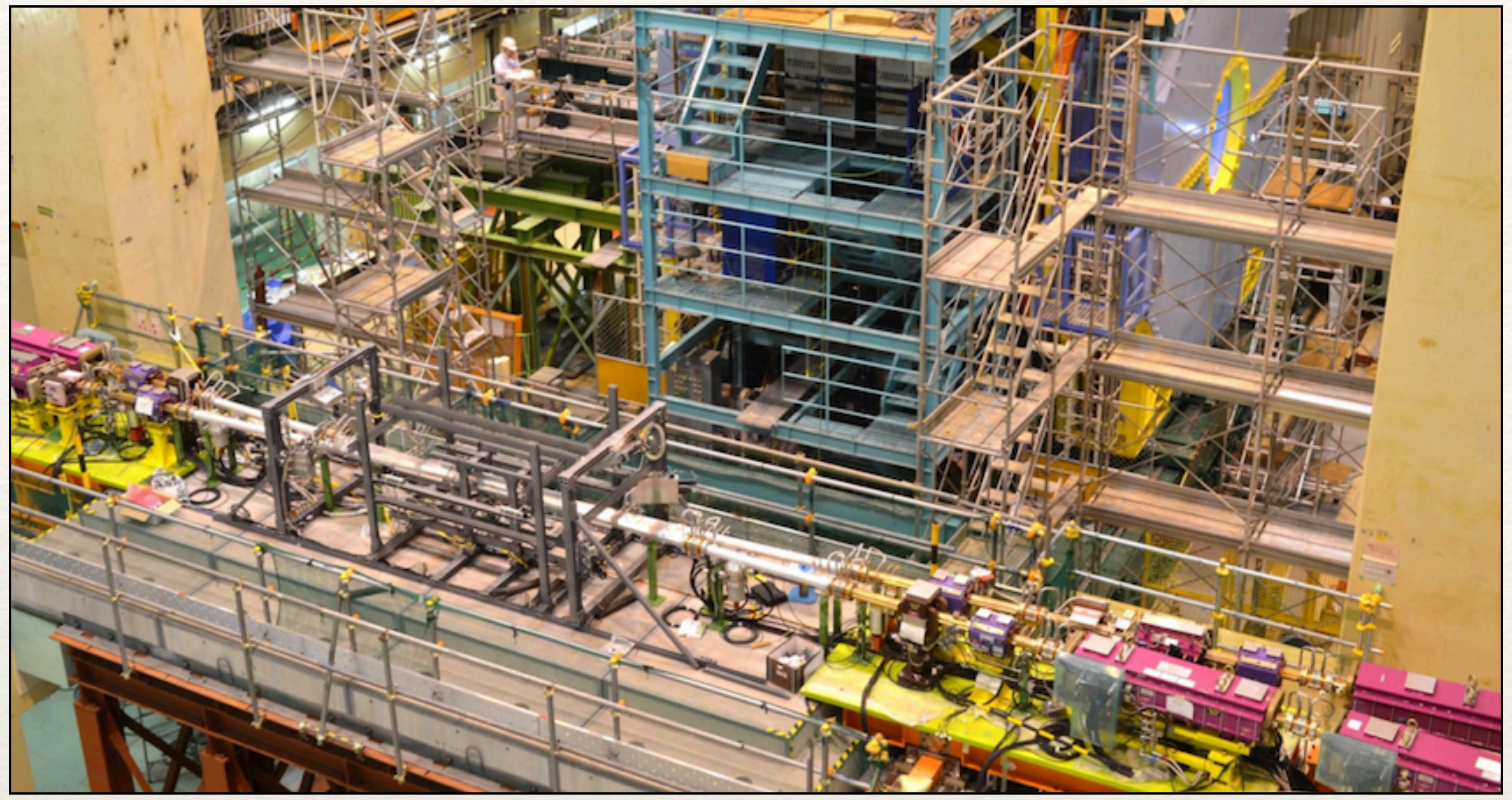
Beryllium beam pipe
20 mm diameter

positrons - 4 GeV (LER)

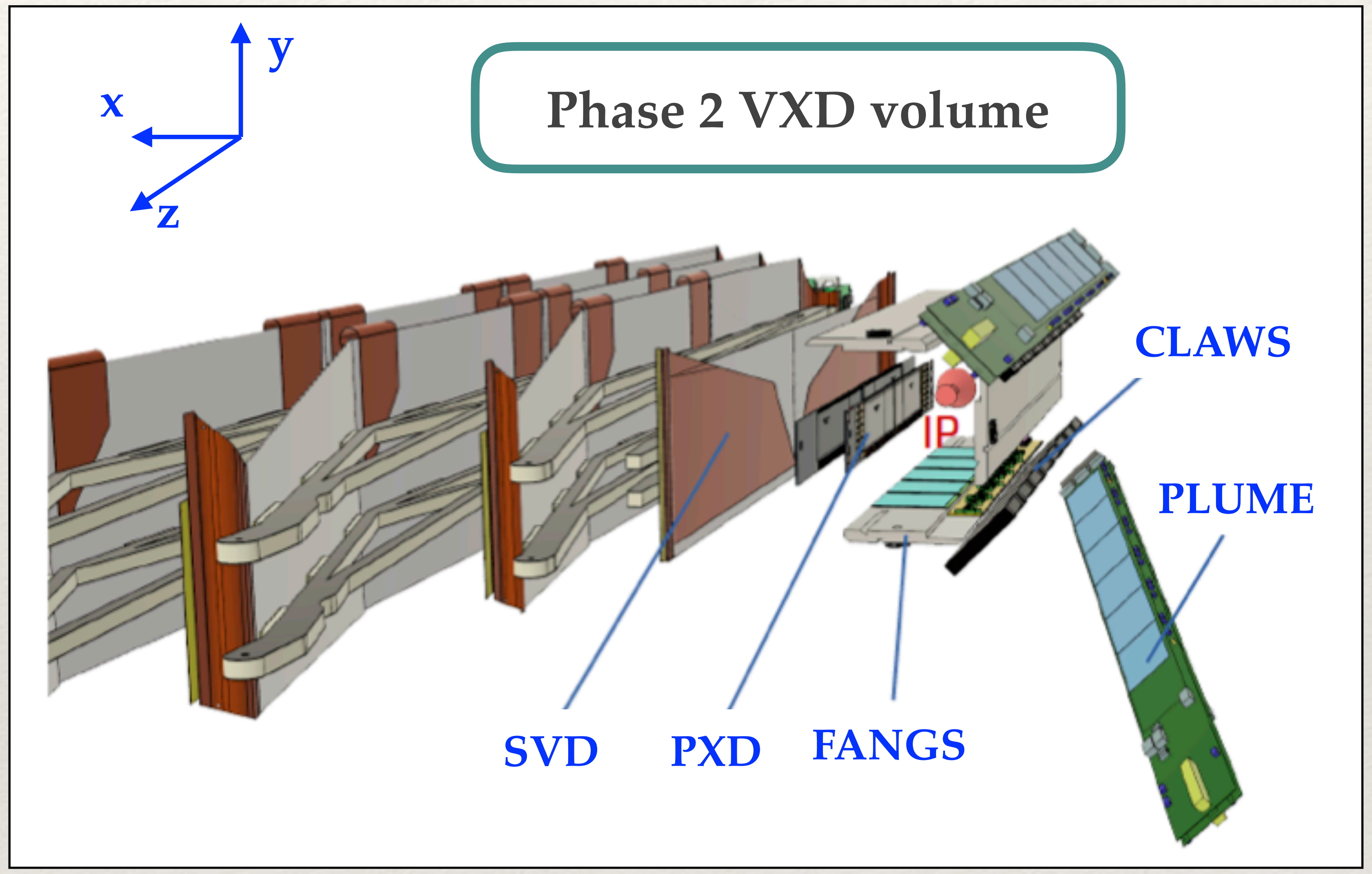
Central Drift Chamber
He (50%) - C_2H_6 (50%)

Vertex Detector
2 layers of DEPFET PiXel Detectors
4 layers of Silicon Strip Detectors

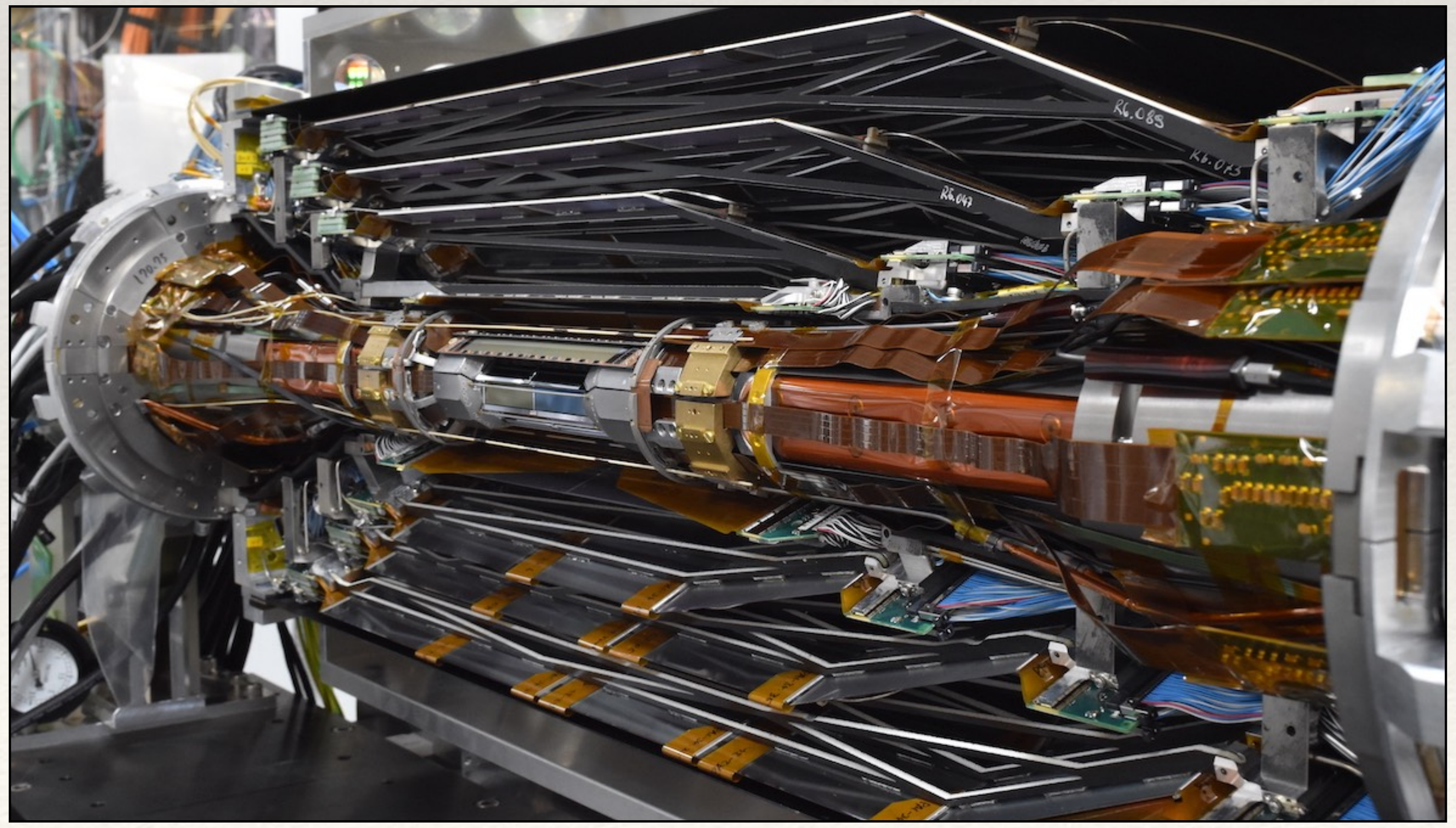
SuperKEKB commissioning



- Phase 1 - 2016: no Belle II detector, no Final Focus system, no collisions. BEAST detectors and first circulating beams.



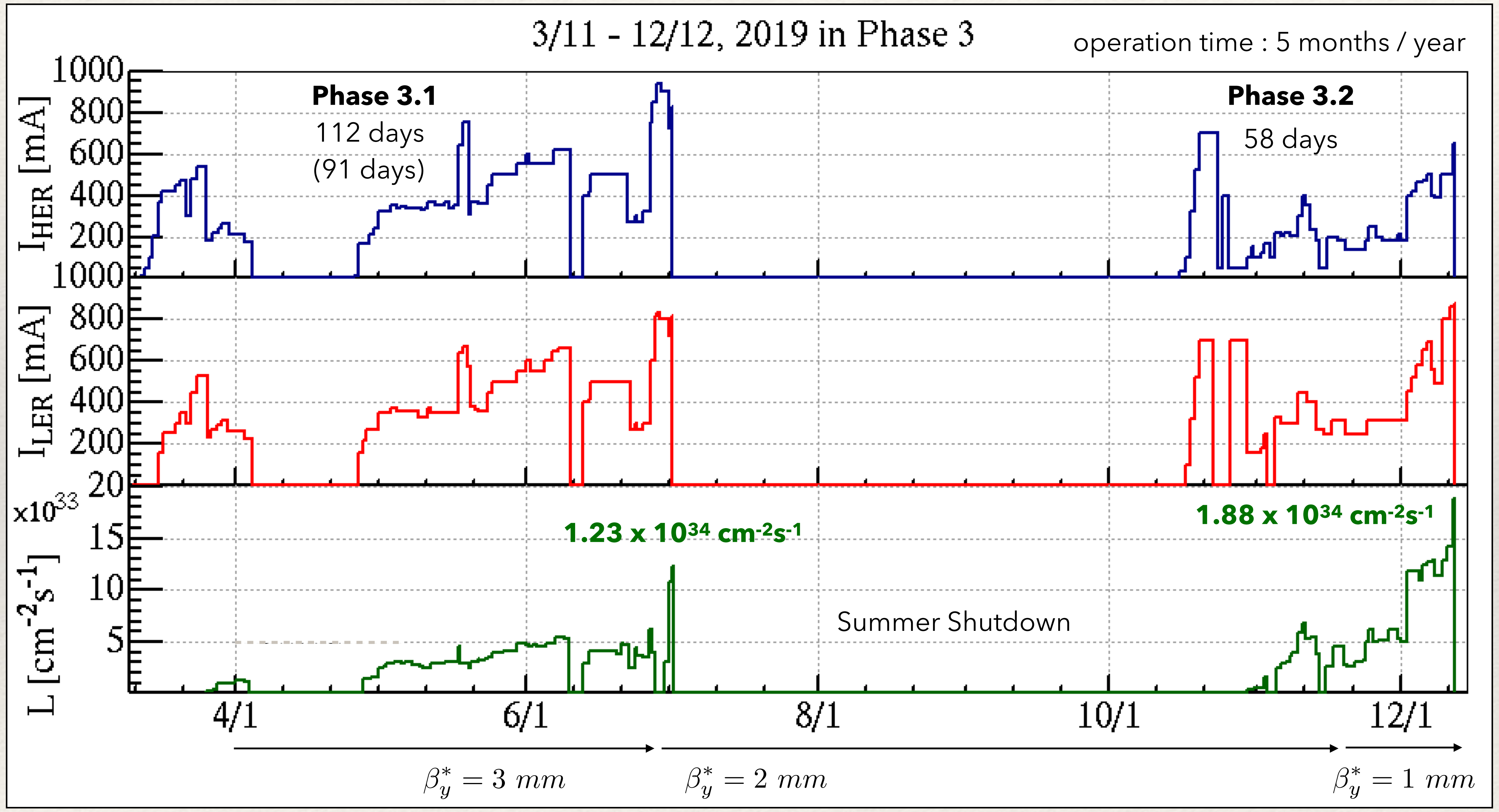
- Phase 2 - 2018: Belle II detector in its final position, BEAST VXD detectors installed, Final Focus system in place, first SuperKEKB collisions, nano beam scheme verified, background evaluation before VXD installation.

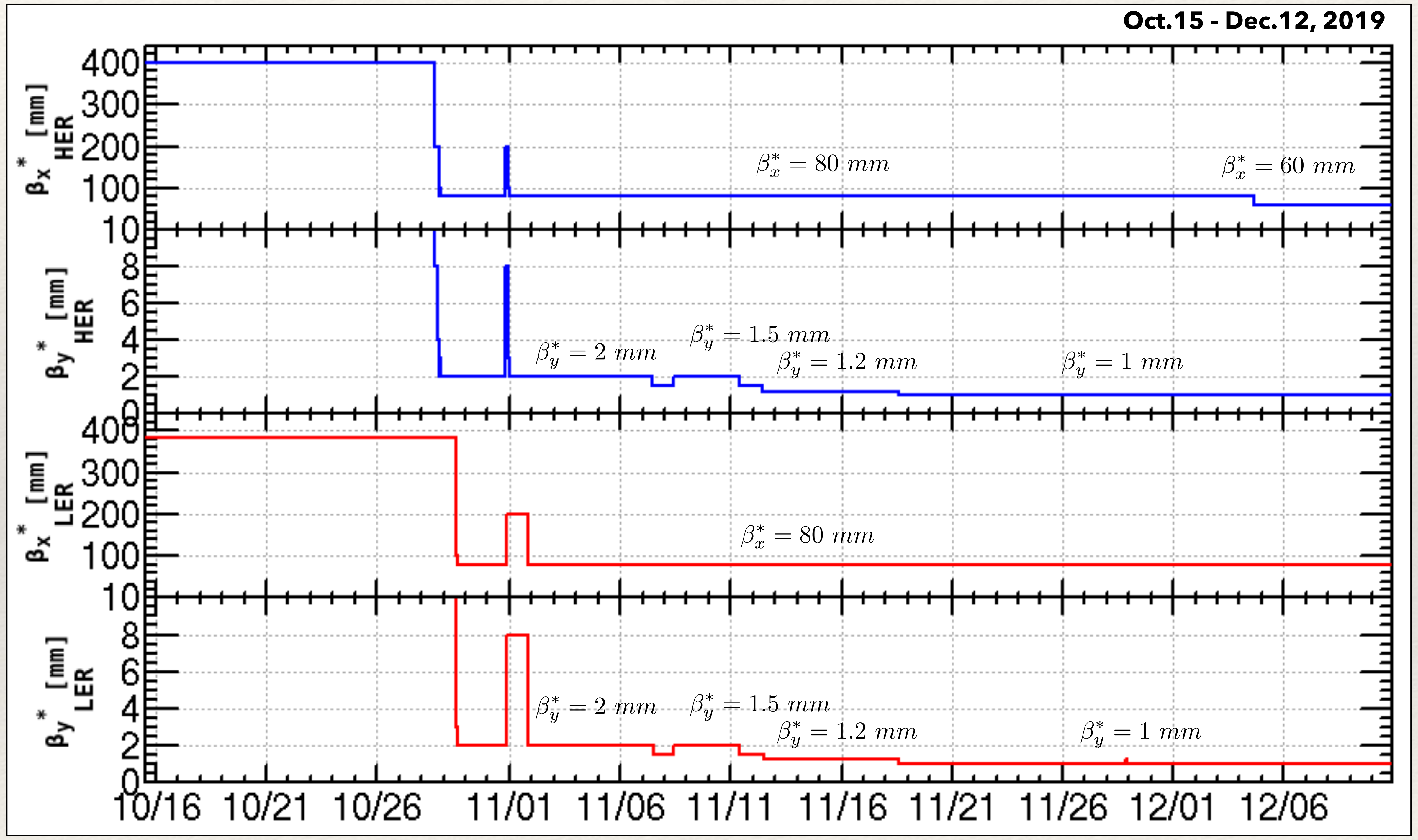


- Early Phase 3 - 2019: VXD detector installed, SuperKEKB in its final configuration, added new collimators, established continuous injection.

Beta function evolution in 2019

- Reached $\beta_y^* = 3$ mm (factor 2 better than KEKB) already in Phase 2
- In Phase 3 squeezed from $\beta_y^* = 3$ mm to $\beta_y^* = 1$ mm
- Actually the smallest β_y^* ever achieved, still a factor 3 to improve.



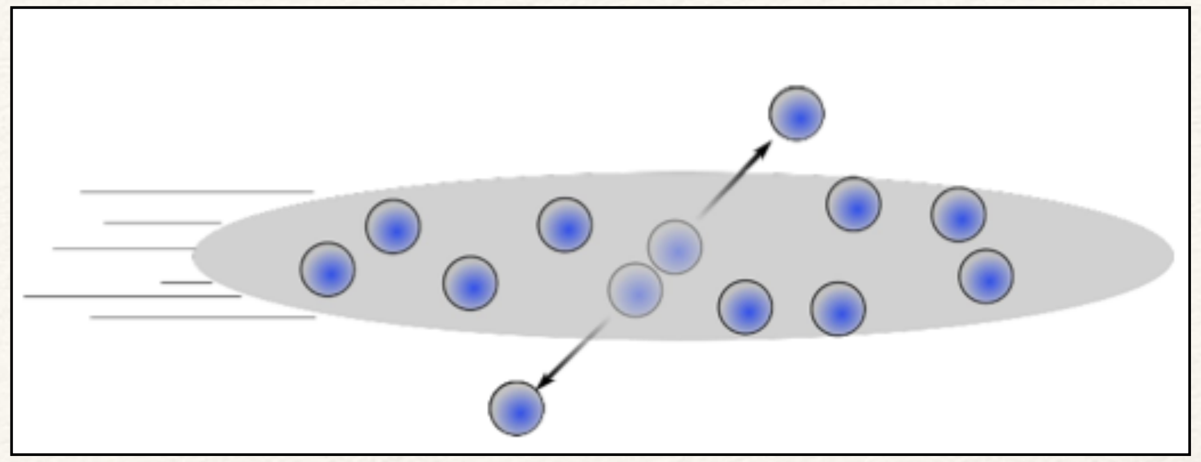


Beta function evolution in 2019

- Reached $\beta_y^* = 3$ mm (factor 2 better than KEKB) already in Phase 2
- In Phase 3 squeezed from $\beta_y^* = 3$ mm to $\beta_y^* = 1$ mm
- Actually the smallest β_y^* ever achieved, still a factor 3 to improve.

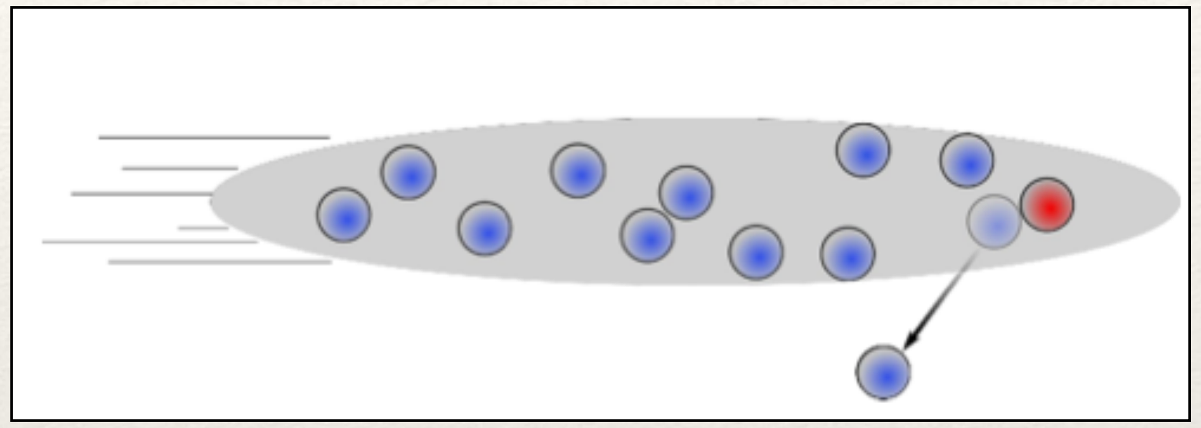
Single beam background sources

Touschek scattering: single Coulomb scattering event between two particles of the same bunch, that are lost.



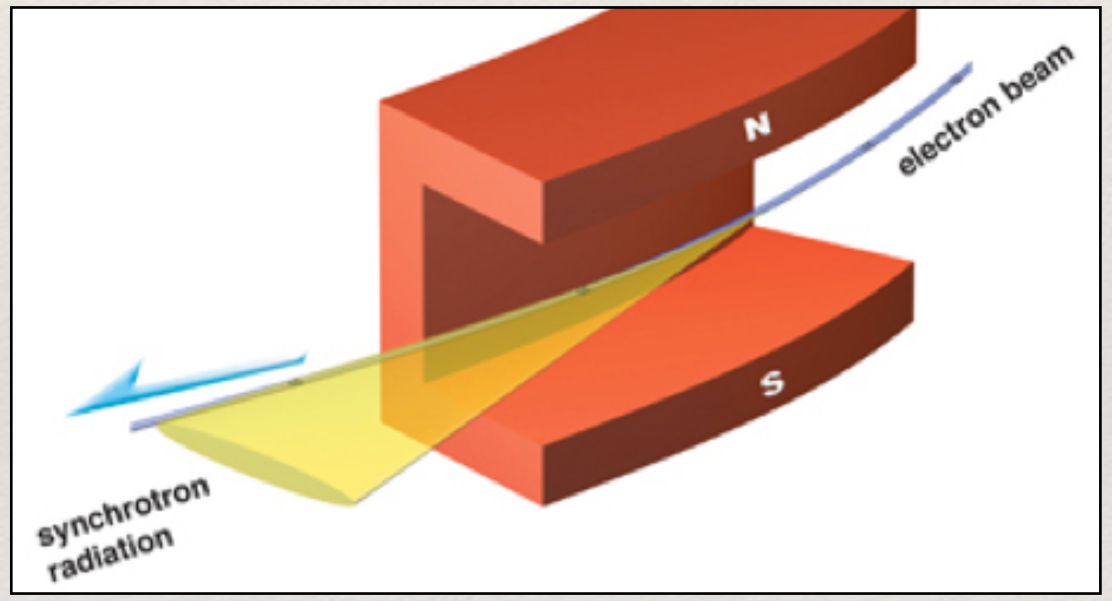
$$R_{Tou} \propto \frac{1}{\sigma E^3 n_b} I_{beam}^2$$

Beam-gas scattering: Coulomb elastic scattering or bremsstrahlung with residual gas atoms.



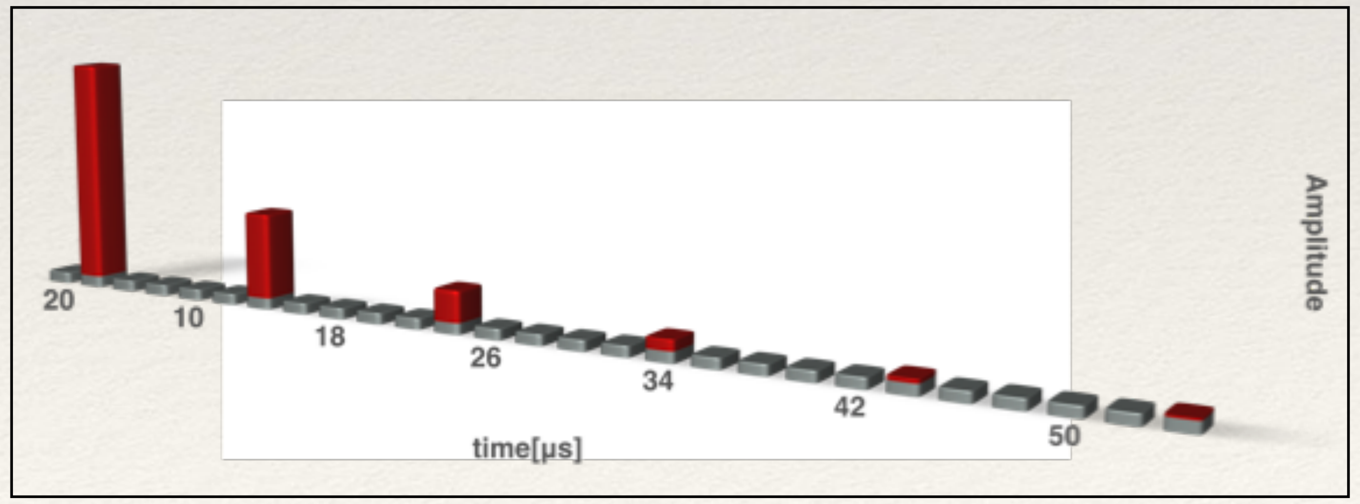
$$R_{bg} \propto I_{beam} P$$

Synchrotron Radiation (SR): photon emission from beam particles when subject to acceleration.



$$W_{SR} \propto \frac{E^4 I_{beam}}{\rho^2}$$

Injection background: injected bunch performing betatron oscillation around the stored bunch, resulting in particle losses especially in the interaction region.

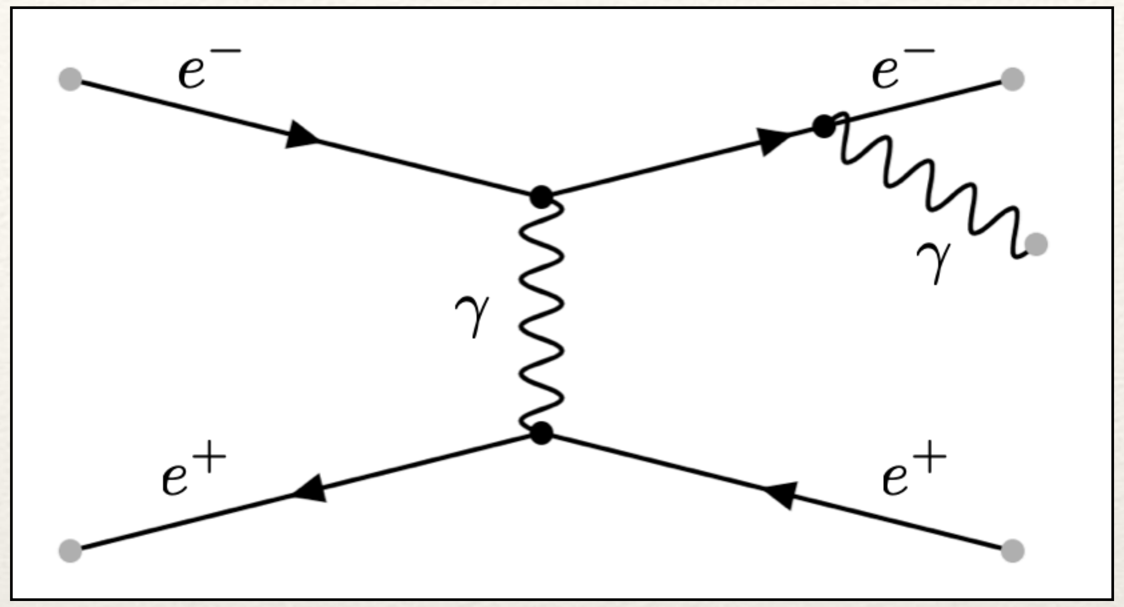


$$R_I \propto R_{inj}$$

Beam-beam background sources

Radiative Bhabha: neutron production from emitted photons (shields used for mitigation); off-energy primary particles lost in final focus magnets.

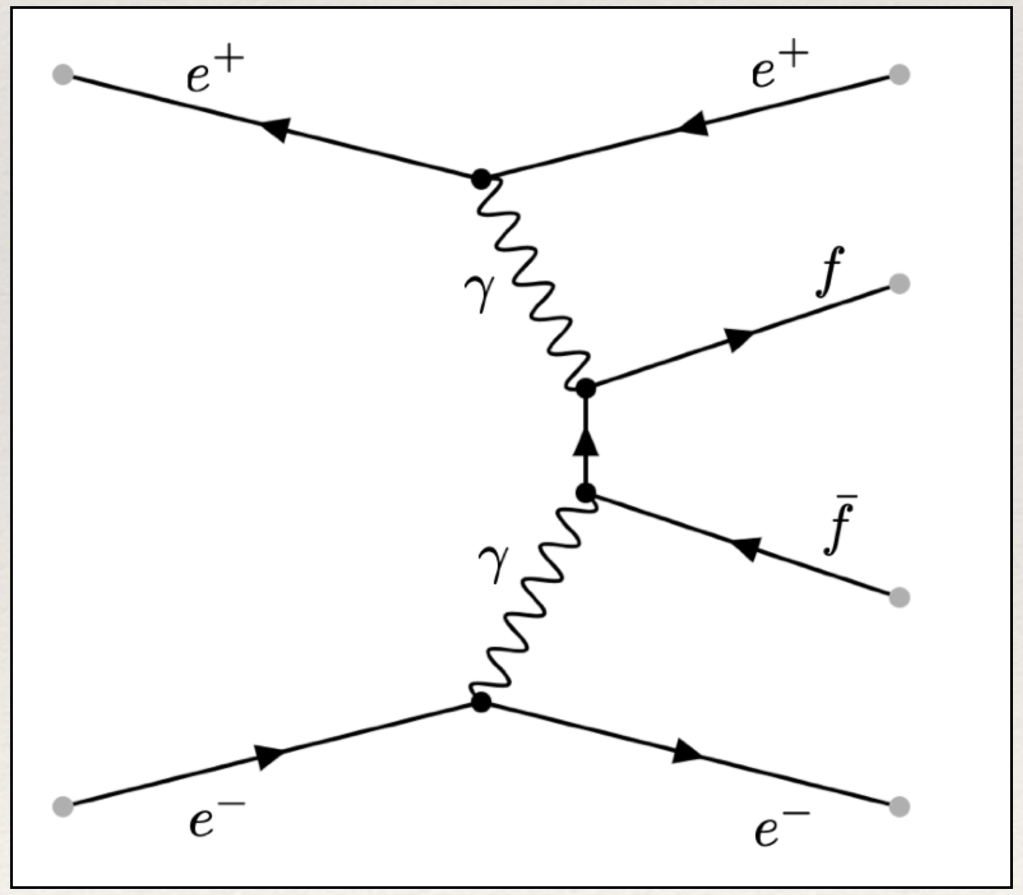
Radiative Bhabha



$R_{RB} \propto L$

Two photons process: low momentum electron-positron pairs that can generate multiple hit in the VerteX Detector.

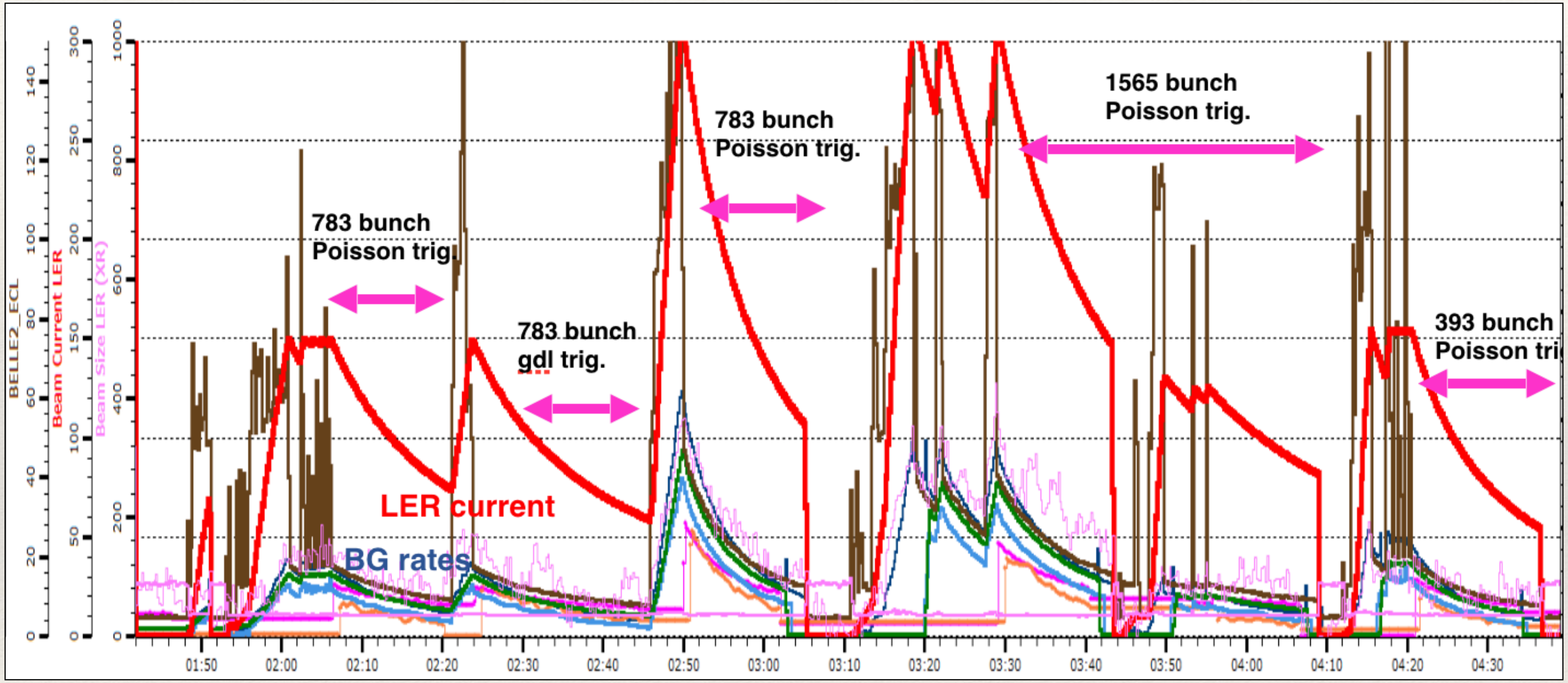
Two photons process

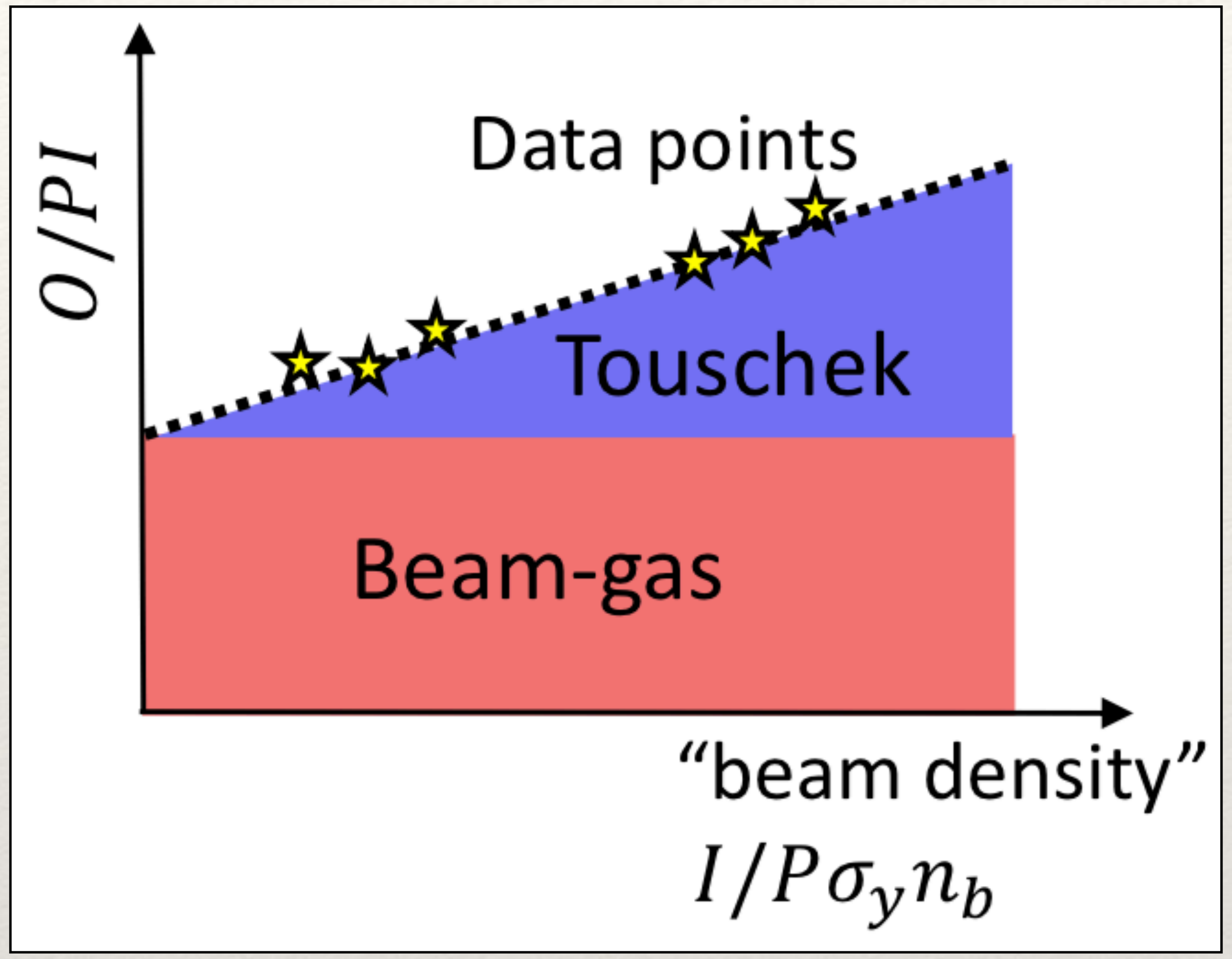


$R_{TP} \propto L$

Single beam background studies

$$Obs. = T \cdot \frac{I^2}{\sigma_y n_b} + B \cdot IPZ_{eff}^2 \quad \longrightarrow \quad \frac{Obs.}{IPZ_{eff}^2} = T \cdot \frac{I}{PZ_{eff}^2 \sigma_y n_b} + B$$





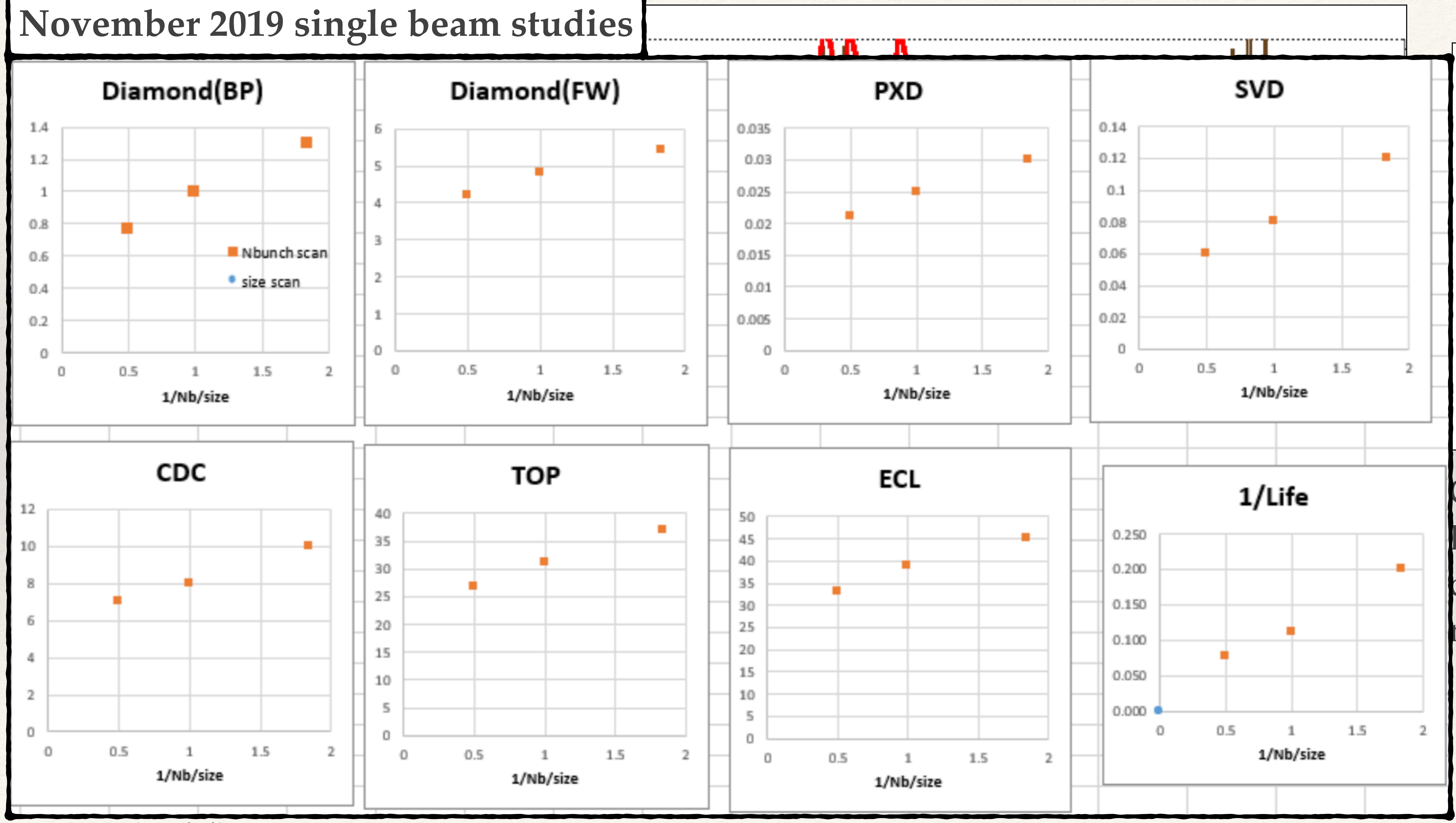
- Constant Z_{eff}
- Pressure re-weighted using cathode pressure gauges measurements in the ring.

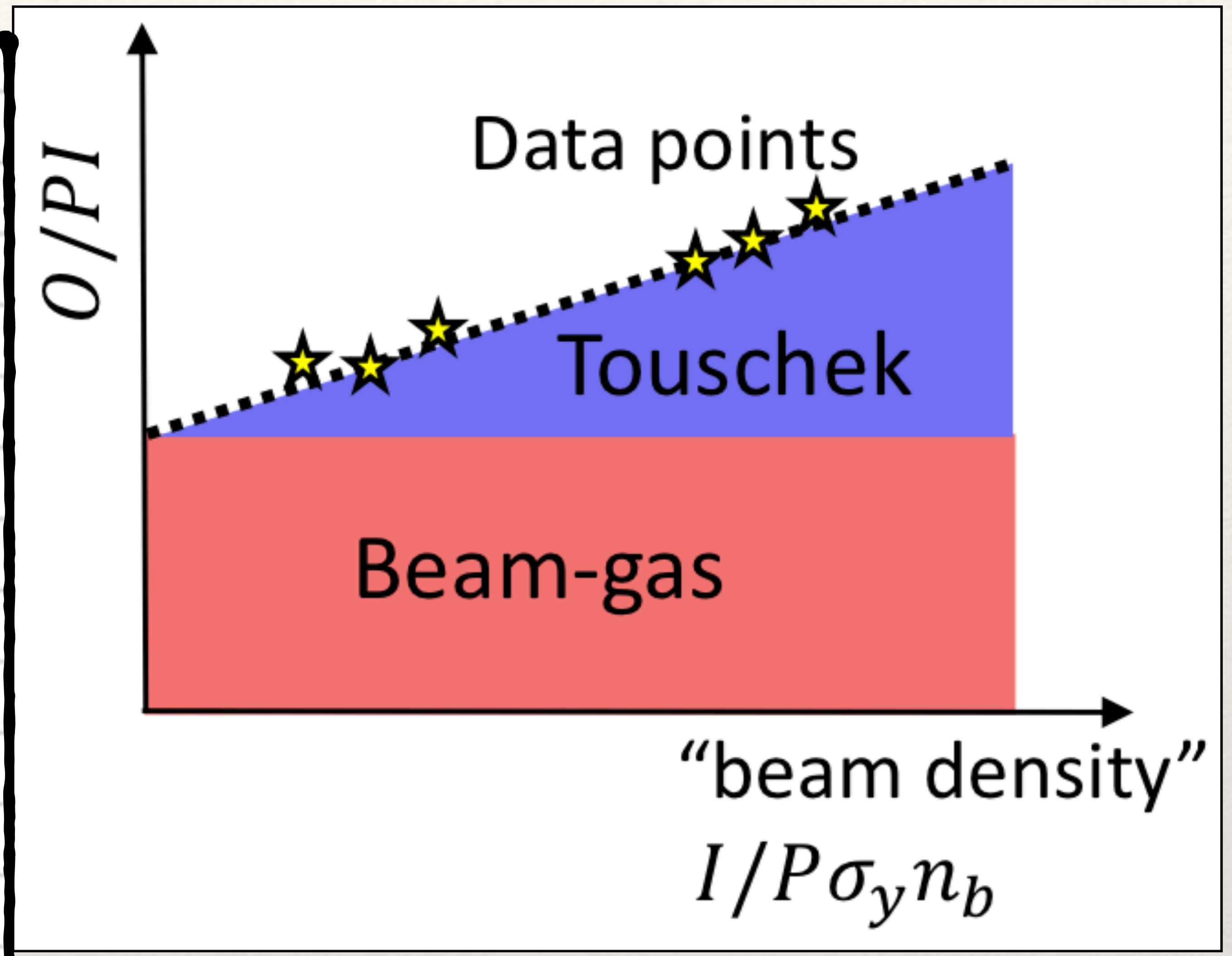
- Change n. of bunches or beam size. Data points will sit (in principle) on a straight line.
- Fit the model to get T and B parameters, and compare with MC predictions.
- Estrapolate background levels to final machine parameters using data/MC ratios.

Single beam background studies

$$Obs. = T \cdot \frac{I^2}{\sigma_y n_b} + B \cdot IPZ_{eff}^2 \quad \longrightarrow \quad \frac{Obs.}{IPZ_{eff}^2} = T \cdot \frac{I}{PZ_{eff}^2 \sigma_y n_b} + B$$

November 2019 single beam studies



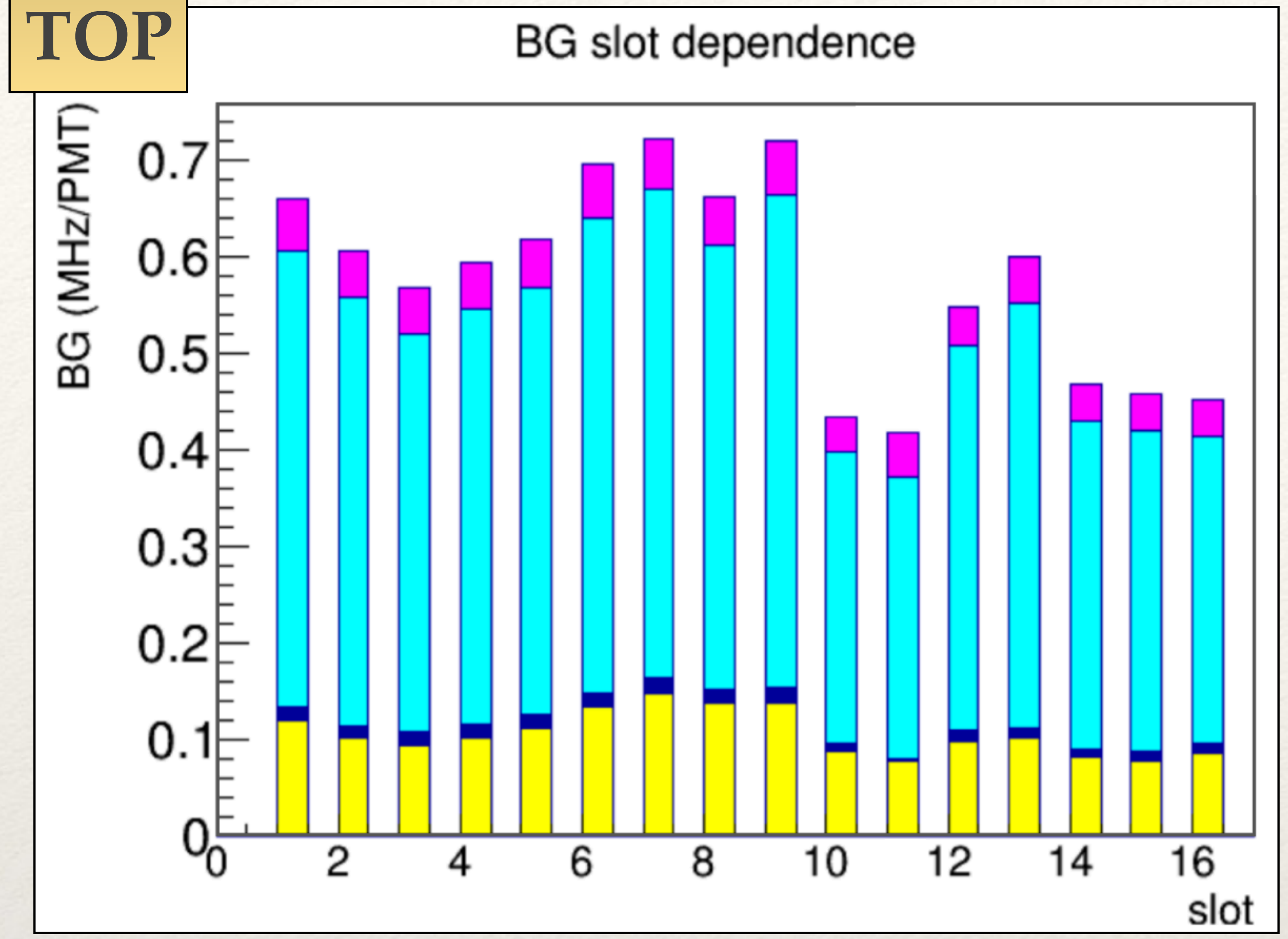


Constant Z_{eff}

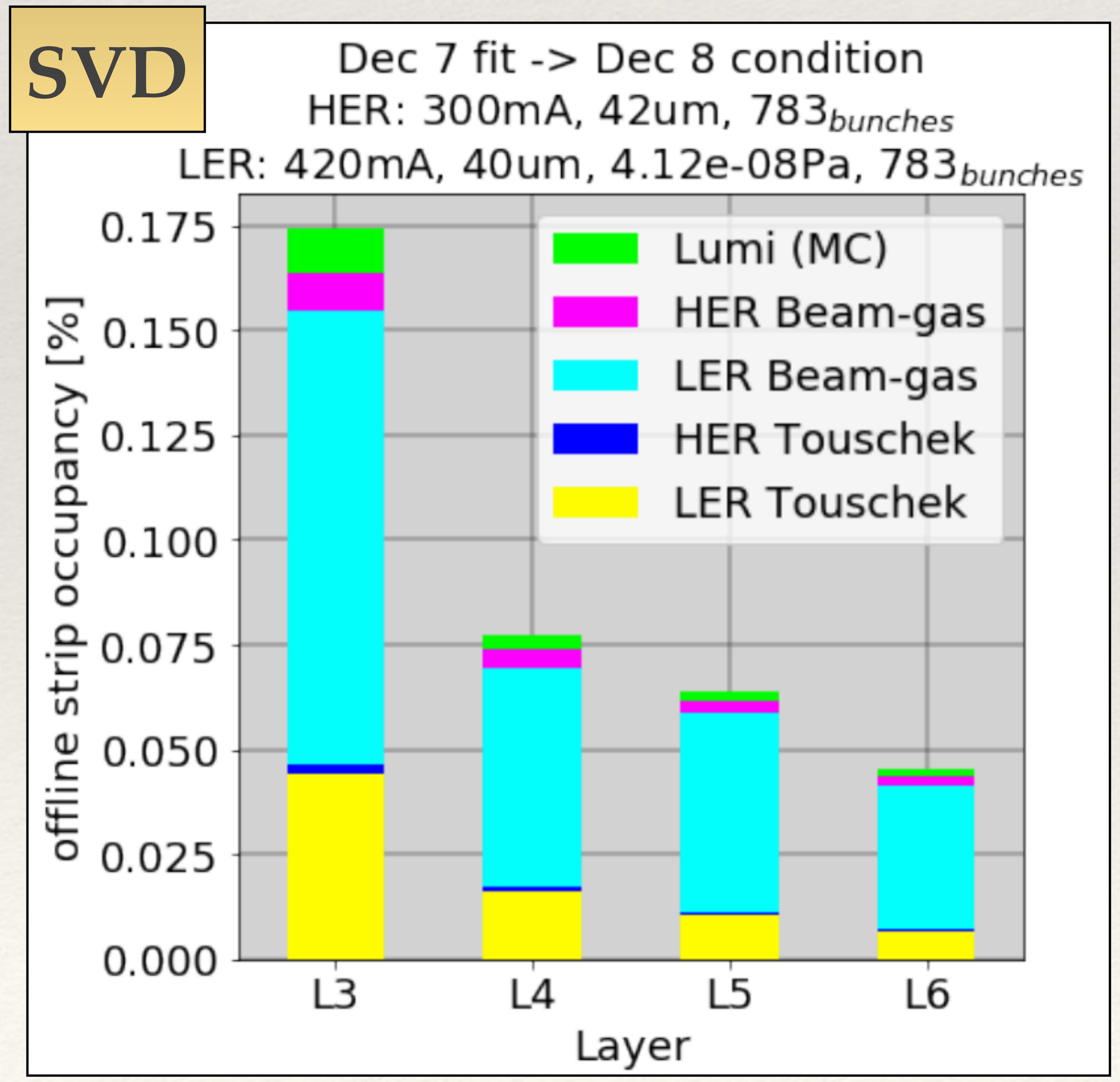
Pressure re-wighted considering cathode pressure gauges measurements in the ring.

Single beam background results

TOP



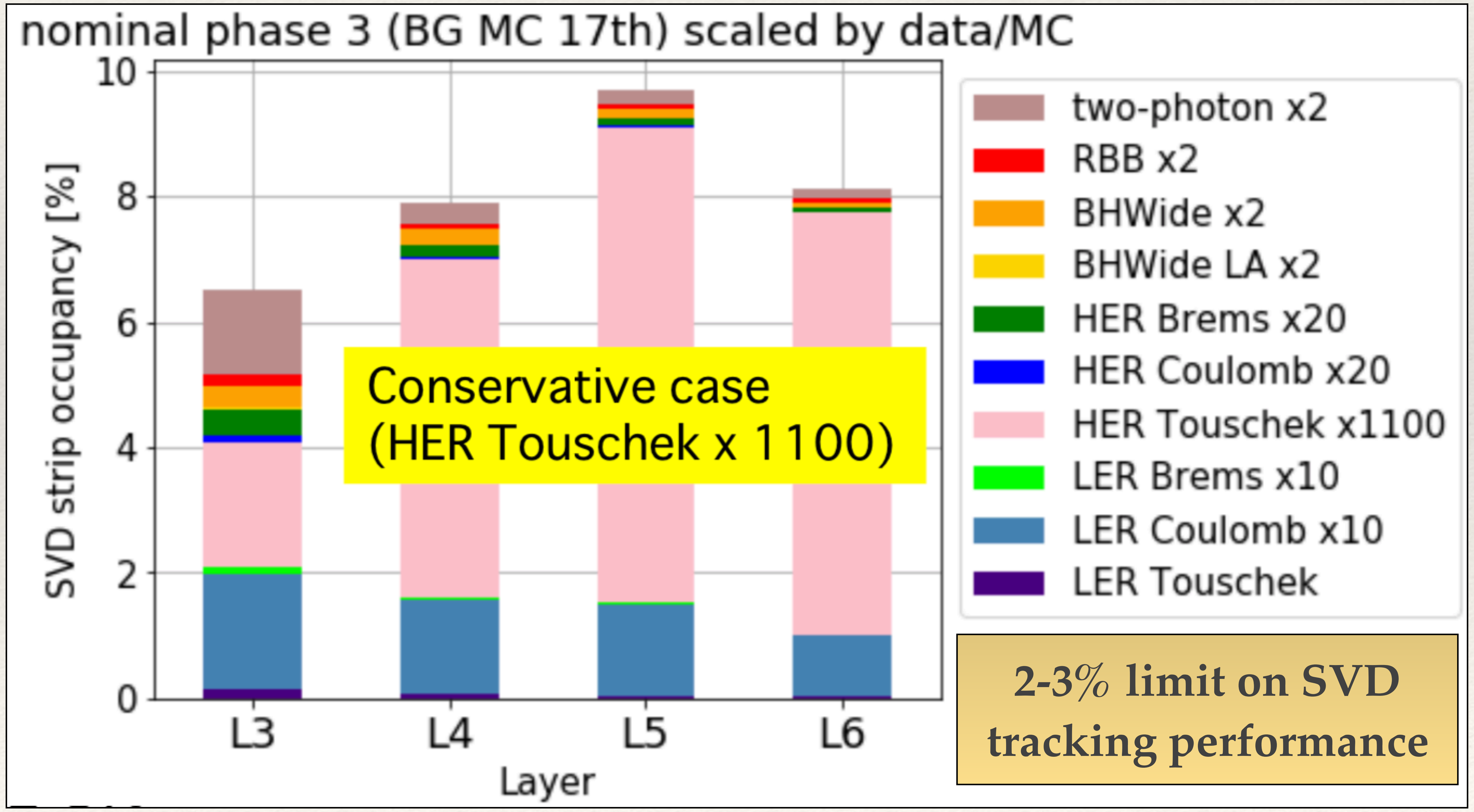
SVD



- LER background dominates, beam-gas being the highest contribution.

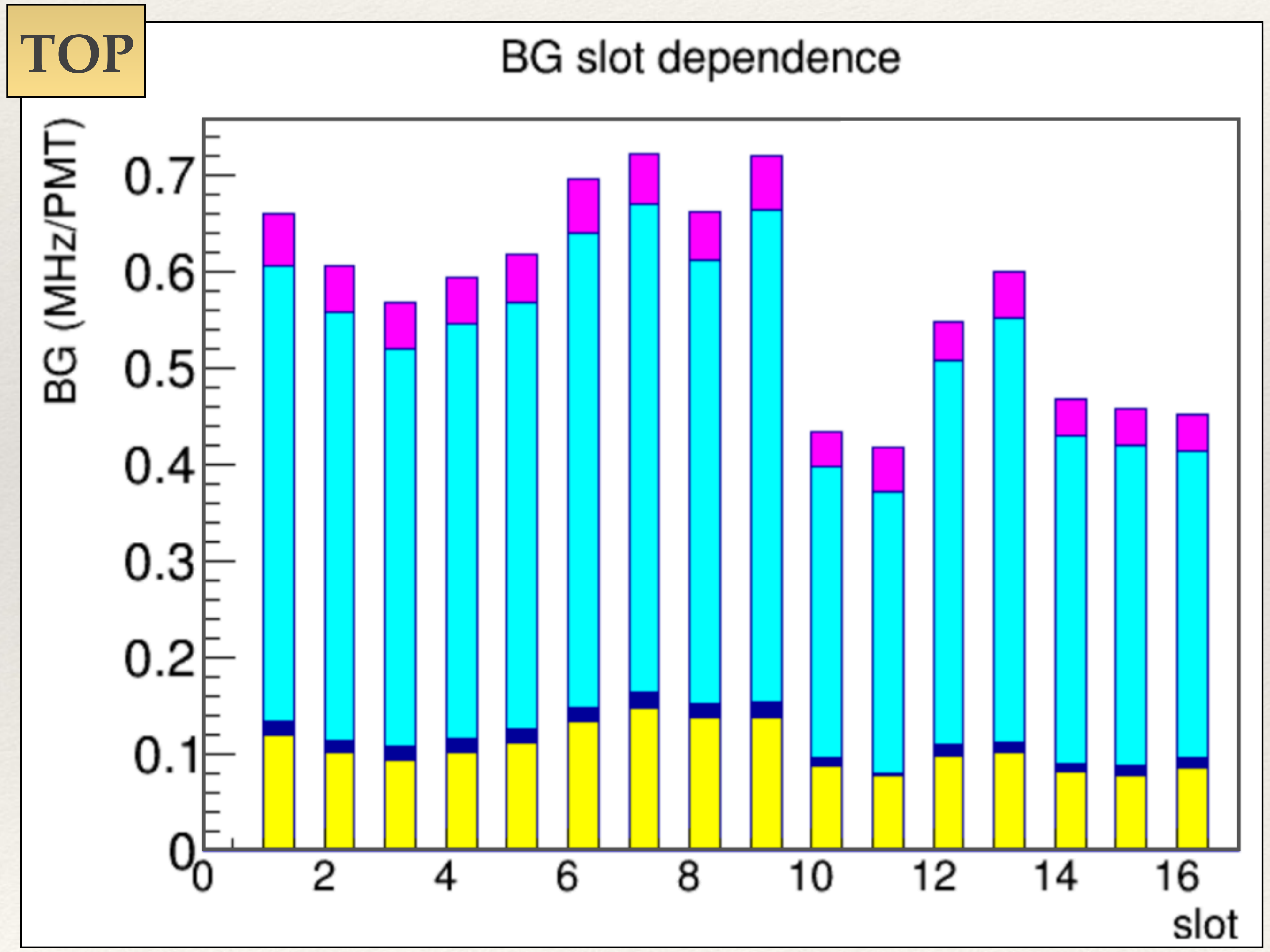
- Comparison with MC gives data/MC ratios, used for BG extrapolation.
- High uncertainties in HER Touschek data/MC ratio.
  - In different studies, data/MC between 1100 and 300.
  - Uncertainty also in BG extrapolation to design parameters.

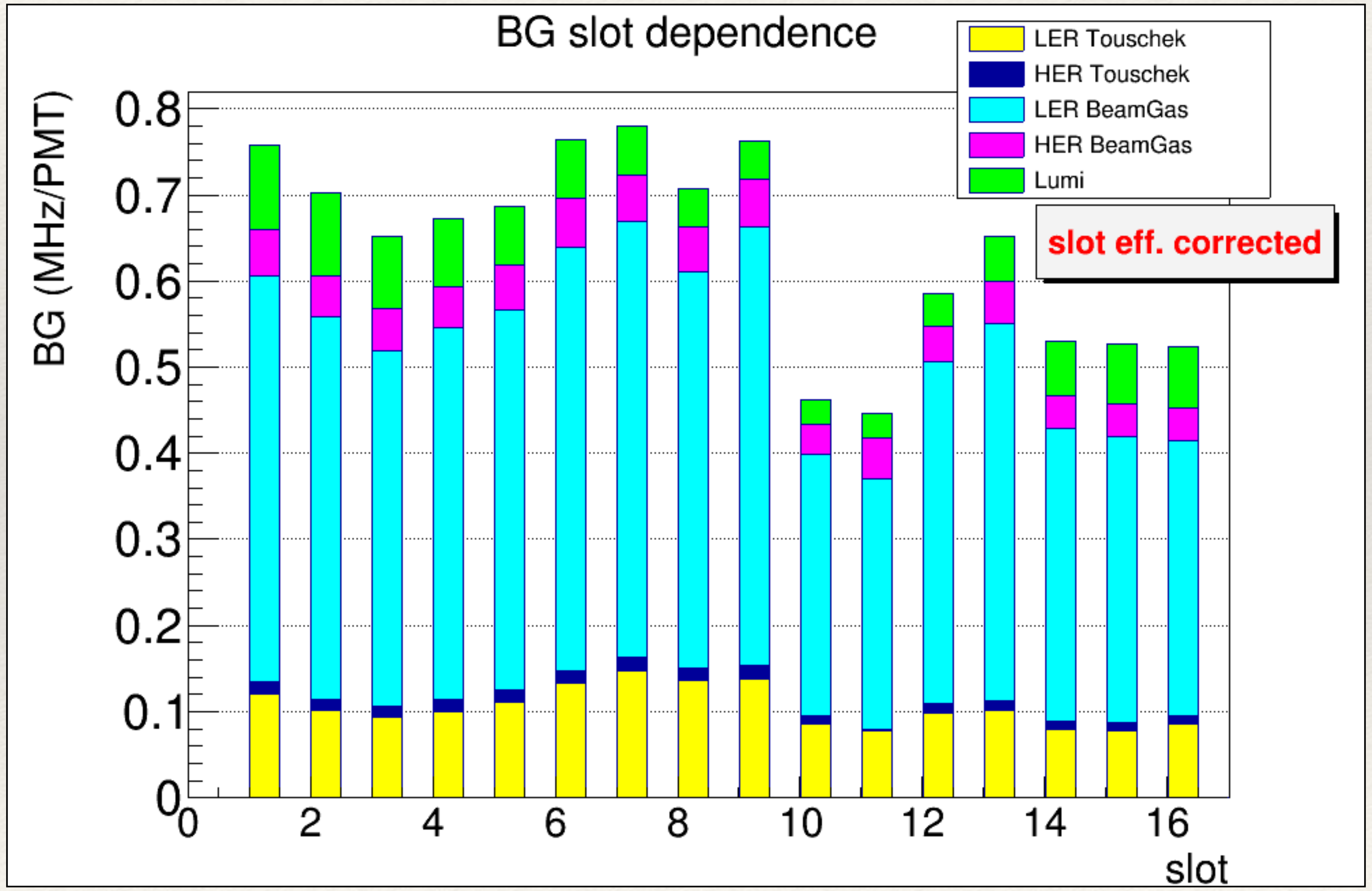
extrapolating to design parameters



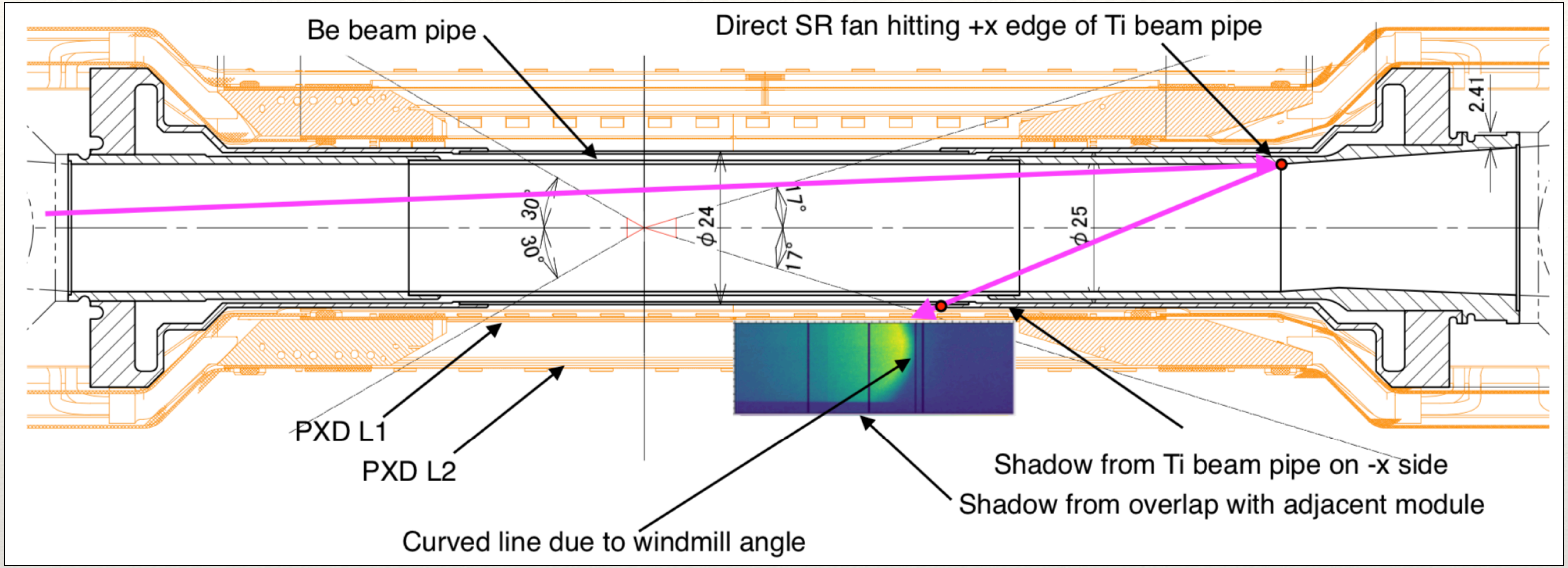
Luminosity background

- Luminosity background evaluated after single beam background subtraction
- Vary luminosity: changing vertical offset between beams, changing n. of bunches, letting beams decay.
  - Different results depending on the method used to change luminosity.
  - Further studies in 2020 runs.
- Background composition: 80% LER, 10% HER, 10% Lumi BG, 60% LER beam-gas
- Present-day limit on TOP PMT rate: 1 MHz





Synchrotron radiation



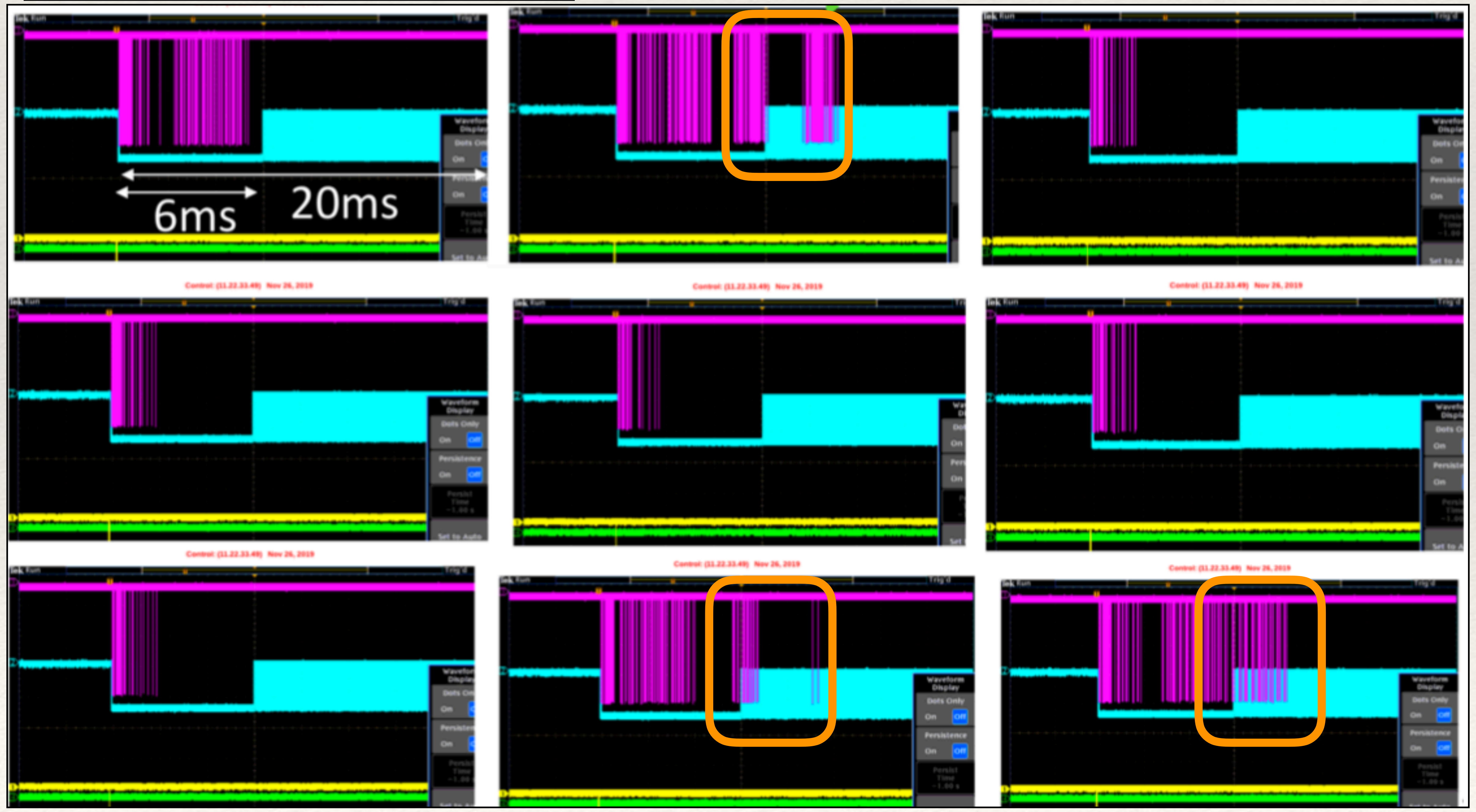
- Synchrotron radiation observed on PXD after last β_x^* squeezing.
- SR photons of injected bunches are backscattered from the edge of Ti beam pipe.
- Can be reduced by changing the beam orbit angle.
- Not fully eliminated, storage component observed, probably caused by increased horizontal dispersion.
- Study in March 2020 already planned to study this additional component.
- New beam pipe design under discussion to protect against back scattered SR photons.

Injection background

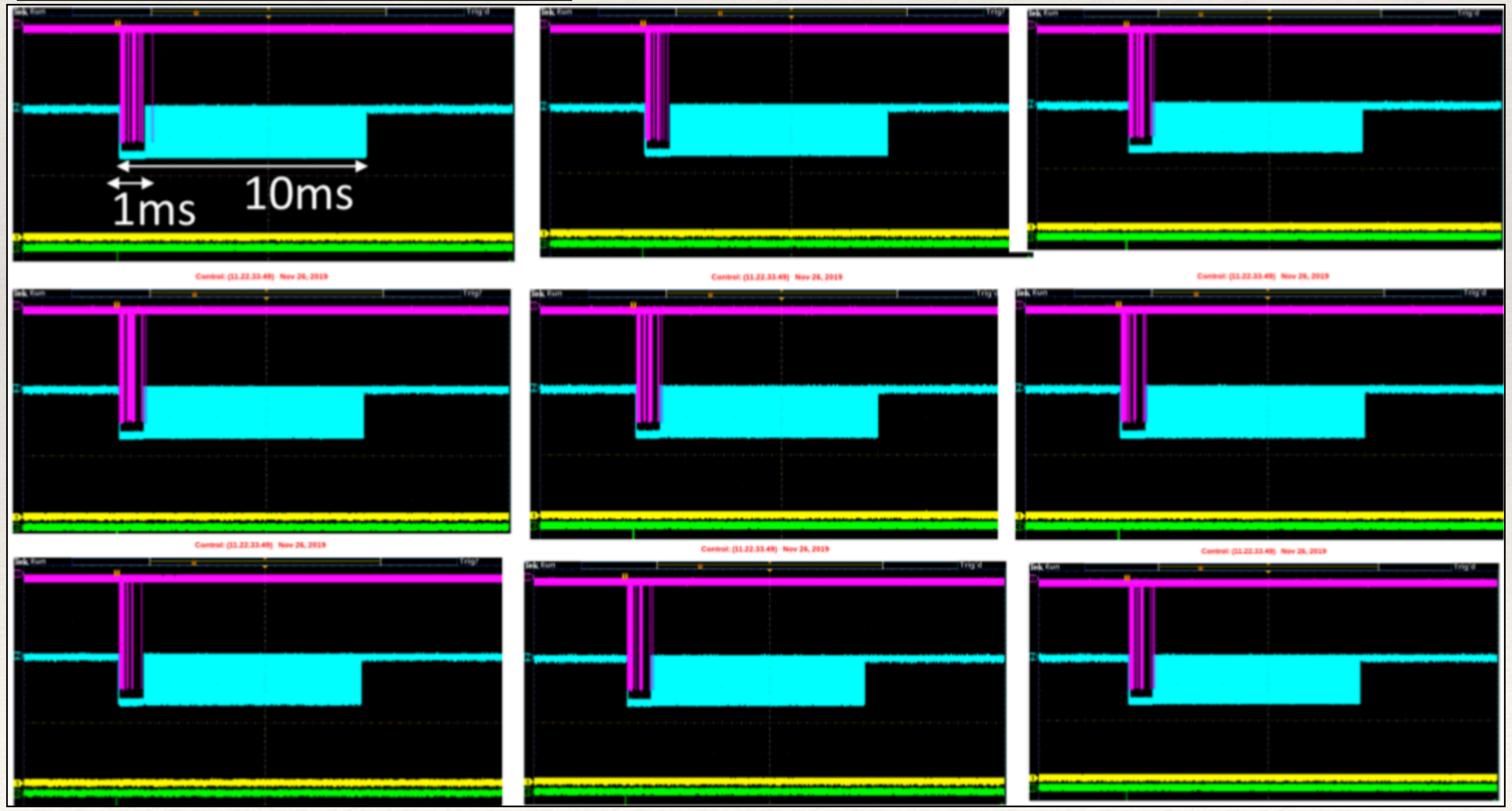
- Injection background observed by ECL: veto window set for injection BG duration.
  - 10 ms window sufficient for HER.
  - LER injection BG lasts up to 20 ms:
    - at 12.5 Hz: 6 ms of **full veto** + 14ms · (3.6μs/10μs) of **gated period** —> 13.75 % DAQ dead time.
  - Long duration of the LER injection BG caused by LER kicker.
- Suppression of injection BG duration needed to reduce dead time.

- ECL trigger E > 20 GeV
- Injection veto
- LER kicker

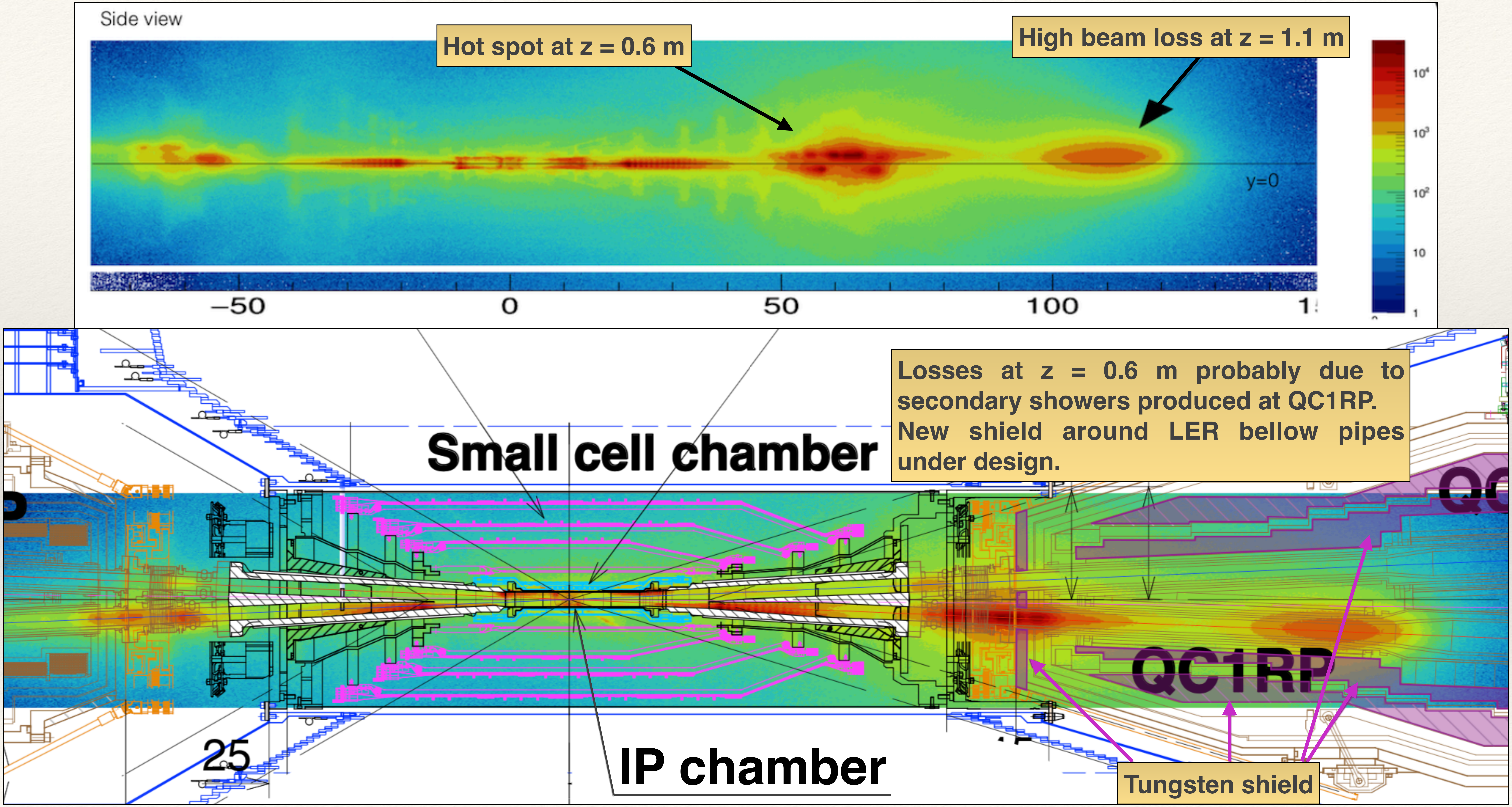
LER injection at 6.25 Hz



HER injection at 6.25 Hz



Two tracks vertices study



Prospects towards 2020 runs

- Compared to 2019 spring run, background levels improved by a factor 2-3
  - ✴️ β_y^* squeezed from 3 mm to 1 mm —> IR background increase
  - ✅ Improved injections, tighter collimators setting possible
  - ✅ Progress in vacuum scrubbing

- Improve data/MC ratios for Touschek and beam-gas (including pressure distribution):
- Include new components in the background simulation: synchrotron radiation, injection, neutrons from radiative Bhabha scattering, inelastic beam-gas scattering at IR.

- New vertical collimator installed in winter shutdown, impact on BG levels to be verified.
- Study of crab waist sextupoles in Spring 2020 run.
- New tungsten shield for LER bellow pipes under design.
- Additional coating of central beam pipe and modification of QCS beam pipe geometry under study.

Conclusions

- Since 2018 systematic studies conducted by Belle II and SuperKEKB groups to understand BG components.
- Big impact of machine induced background on the Belle II detector:
  - TOP (PMTs), CDC (leakage current), PXD (SR and occupancy), SVD (occupancy).
- LER beam-gas is the dominating BG contribution
  - Vertical collimators essential to reduce this BG component
- Simulation to be improved. Reduction of data/MC ratios allows a more reliable BG extrapolation at design parameters.

- Challenging road towards design luminosity:
  - still factor ~3 of reduction in β_y^*
  - still a factor ~4 of increase in beam currents
  - background levels acceptable for 2020 runs, to be improved for next runs.

Thank you

BACKUP

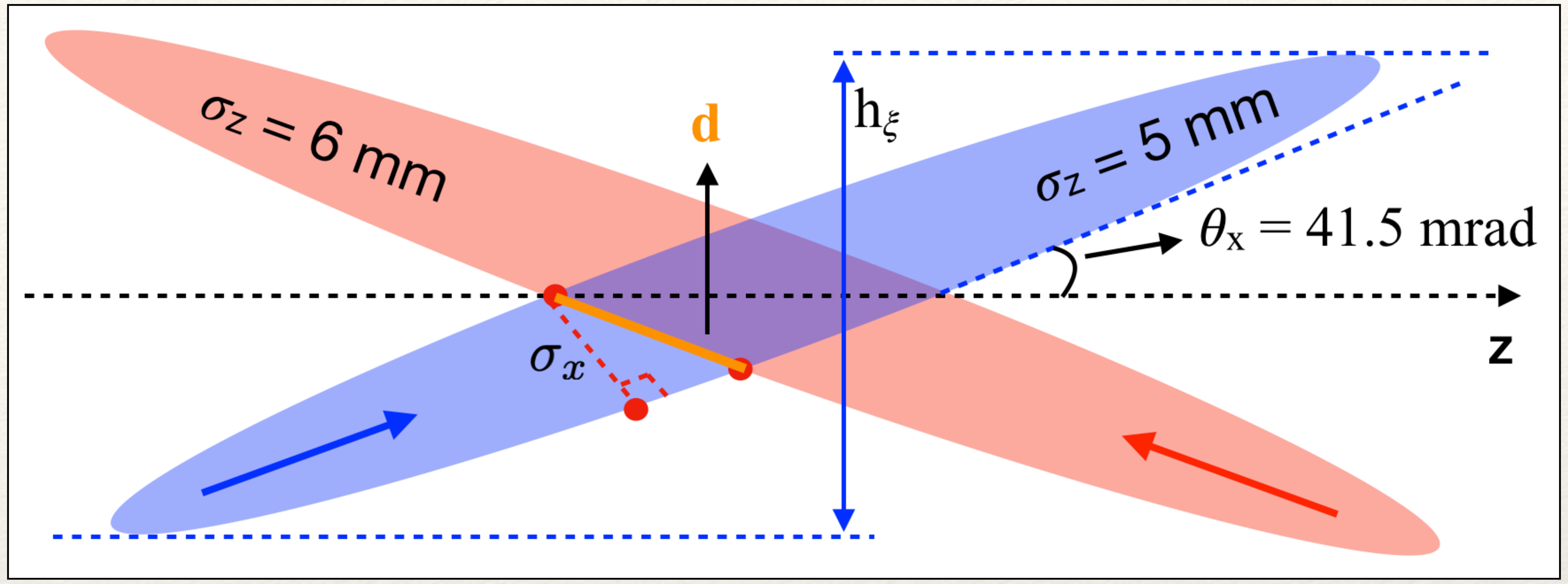
KEKB - SuperKEKB parameters

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

$$\phi_{Piw} = \frac{\sigma_z}{\sigma_x^*} tan\theta_x$$

Hourglass effect condition:

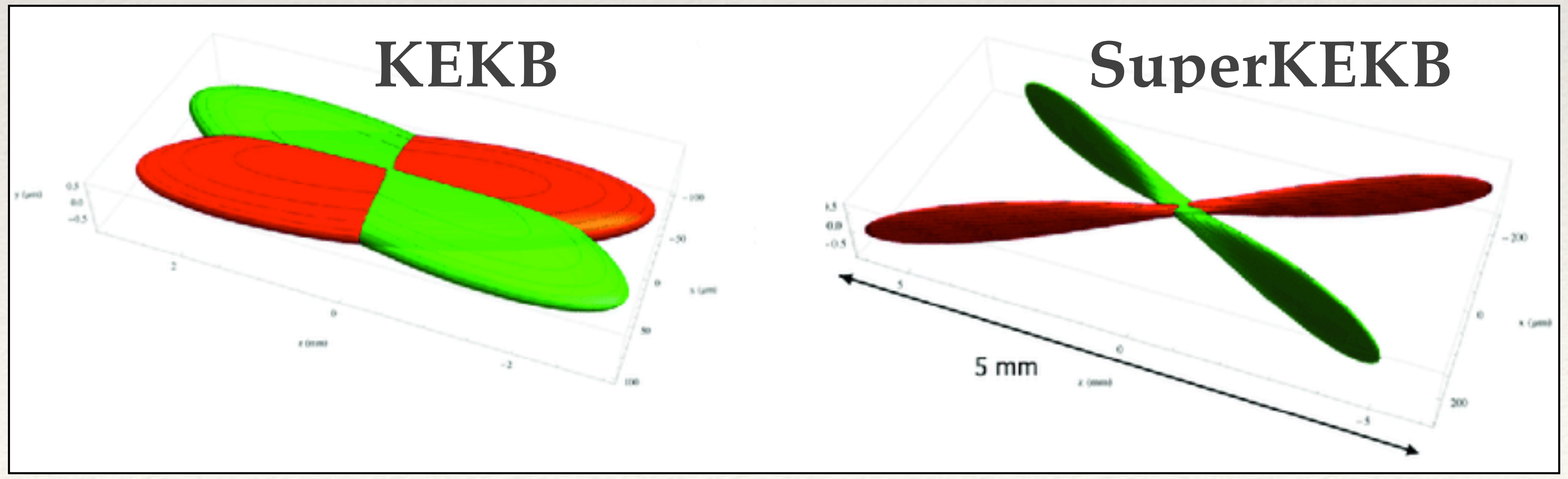
$$\beta_y^* \geq d = \frac{\sigma_x^*}{sin(2\theta_x)}$$



	KEKB		SuperKEKB	
	LER	HER	LER	HER
E [GeV]	3.5	8.0	4.0	7.0
θ_x [mrad]	0 (11)		41.5	
ε_x [nm]	18	24	3.2	4.6
ε_y [pm]	150	150	8.64	12.9
β_x^* [mm]	1200	1200	32	25
β_y^* [mm]	5.9	5.9	0.27	0.30
σ_x^* [μm]	147	170	10.1	10.7
σ_y^* [nm]	940	940	48	62
n_b	1584		2500	
I [A]	1.64	1.19	3.6	2.6
L [cm^{-2} s^{-1}]	2.1 x 10^{34}		8.0 x 10^{35}	

$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp\beta_y^*}{\sigma_y^*(\sigma_x^* + \sigma_y^*)}R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$



HER new model for Fall 2019 run

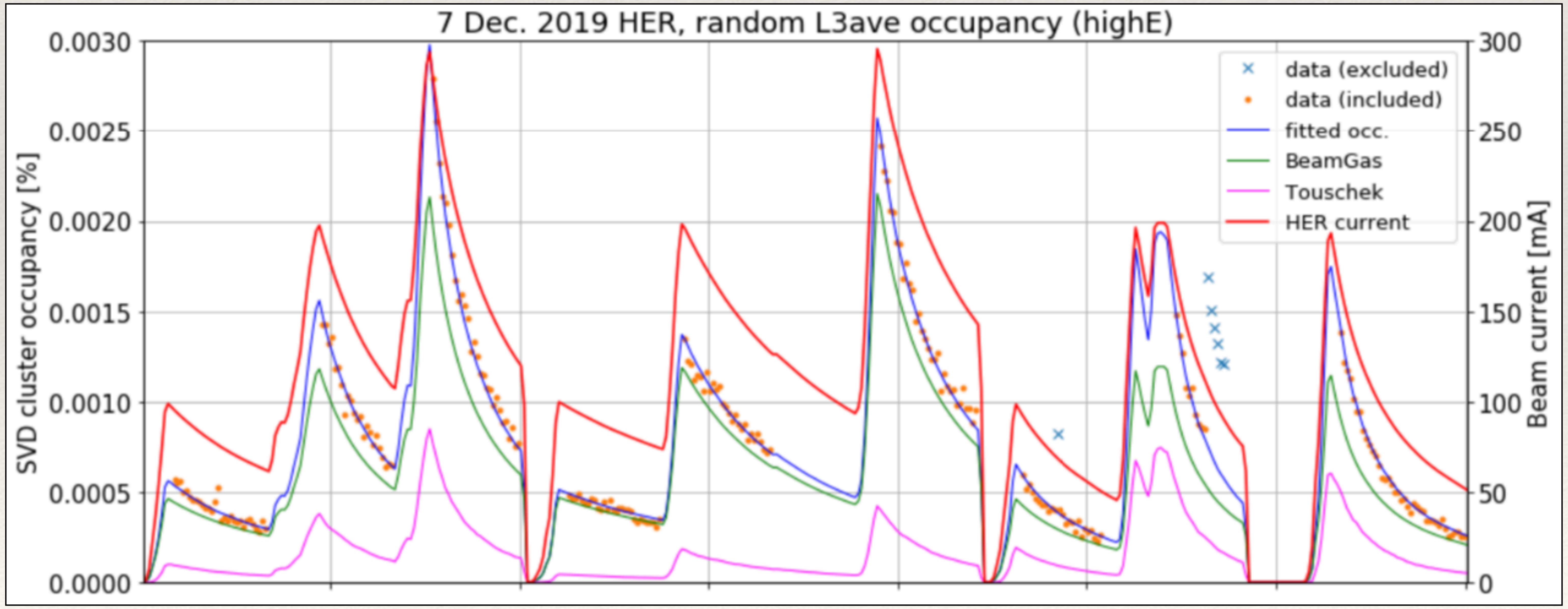
- Initial simple heuristic fit with two fit parameters:

$$Obs = T \cdot \frac{I^2}{\sigma_y n_b} + B \cdot IPZ_{eff}^2 \quad \text{with} \quad P = P_0 + \lambda P_{dyn} = \lambda P_{CCG} - (\lambda - 1)P_0$$

- CCG are hitting the lower limit of pressure measurement (1×10^{-8} Pa)
- Replacing P with $P = P_0 + k \cdot I$.
- Change to a three parameters fit, inserting P_0 and k:

$$Obs = T \cdot \frac{I^2}{\sigma_y n_b} + (kB) \cdot I^2 + (P_0 B) \cdot I$$

- Using constant average pressure, P_0 is overestimated and k is underestimated.
- In the three fit parameter model, pressure becomes a fit parameter.
- HER data matched by the new model.

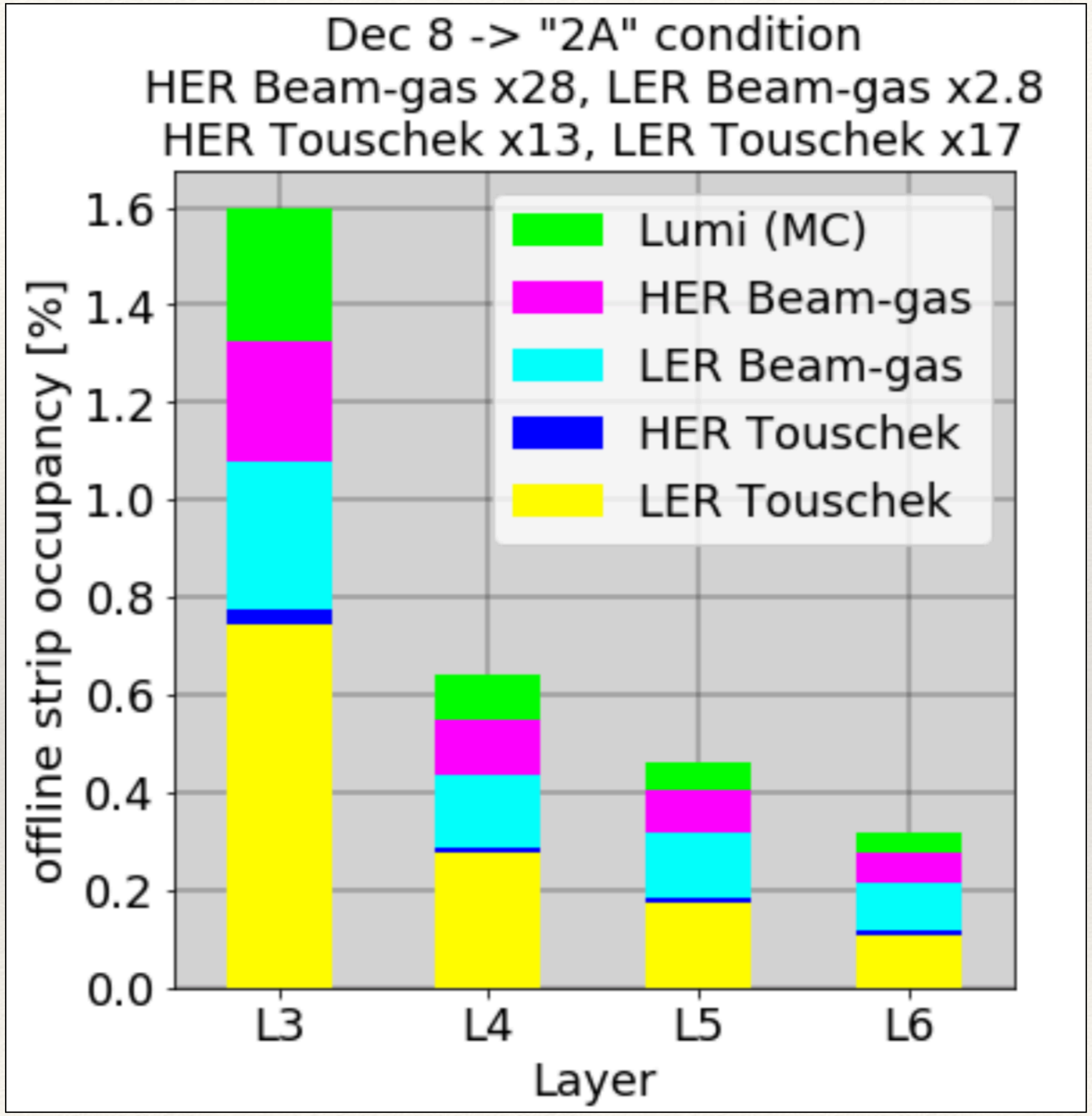


2A scenario

SVD extrapolation to a possible “2 Ampere” scenario

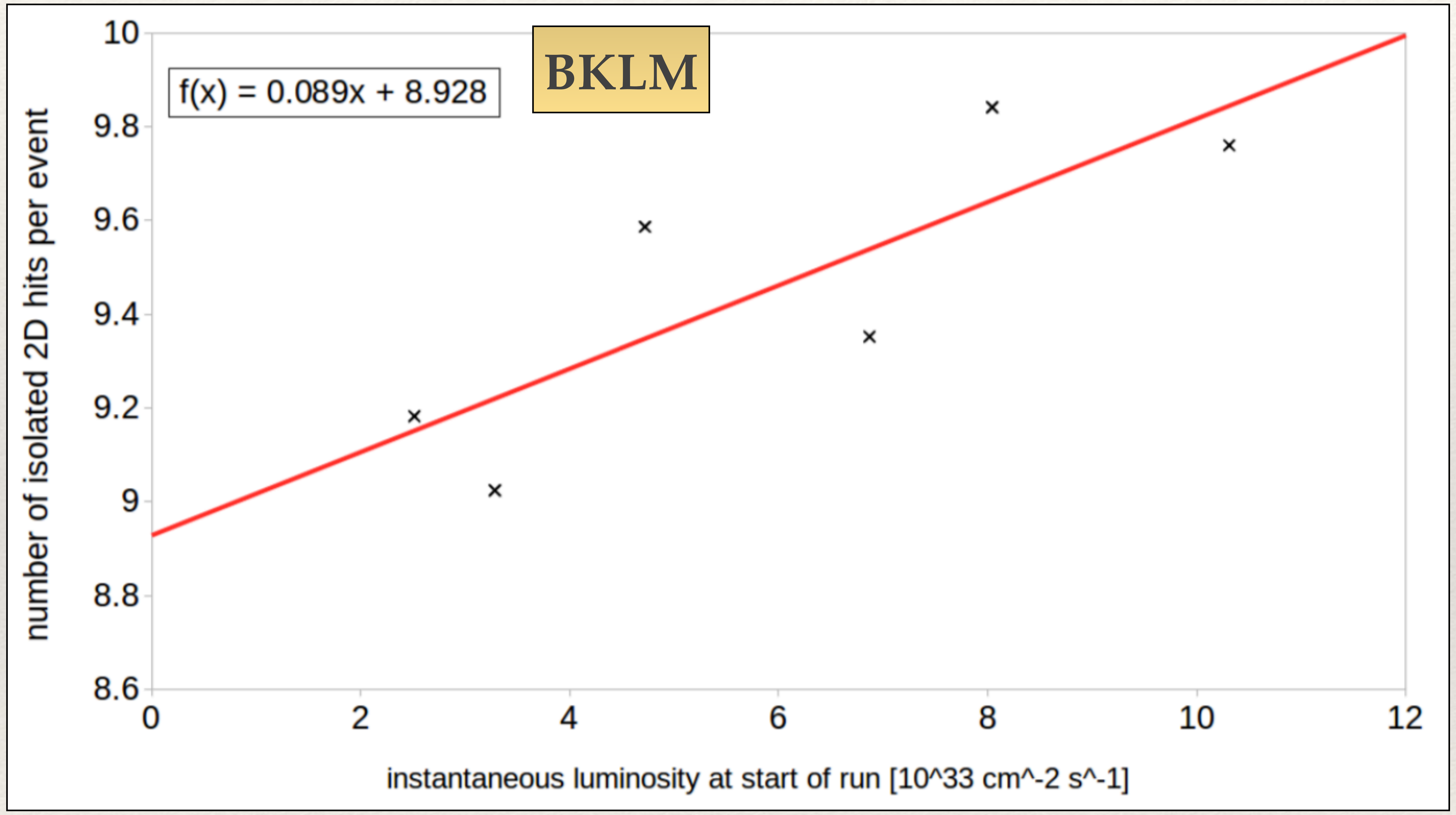
- $I_{LER} = 2.5$ A
  $I_{HER} = 1.6$ A
- 2500 bunches
- $L = 2 \times 10^{35}$ $cm^{-2}s^{-1}$
- $(dP/dI)_{LER}$ $\times 1/10$
  $(dP/dI)_{HER}$ $\times 1/2$
- $\sigma_y \times 0.66$
- LER Beam-gas $\times 1/2.5$
  - reduction by adding D06V1
- Beam-gas $\times 2$ ($\beta_y^* = 1$ mm —> $\beta_y^* = 0.5$ mm)

2-3% limit on SVD tracking performance

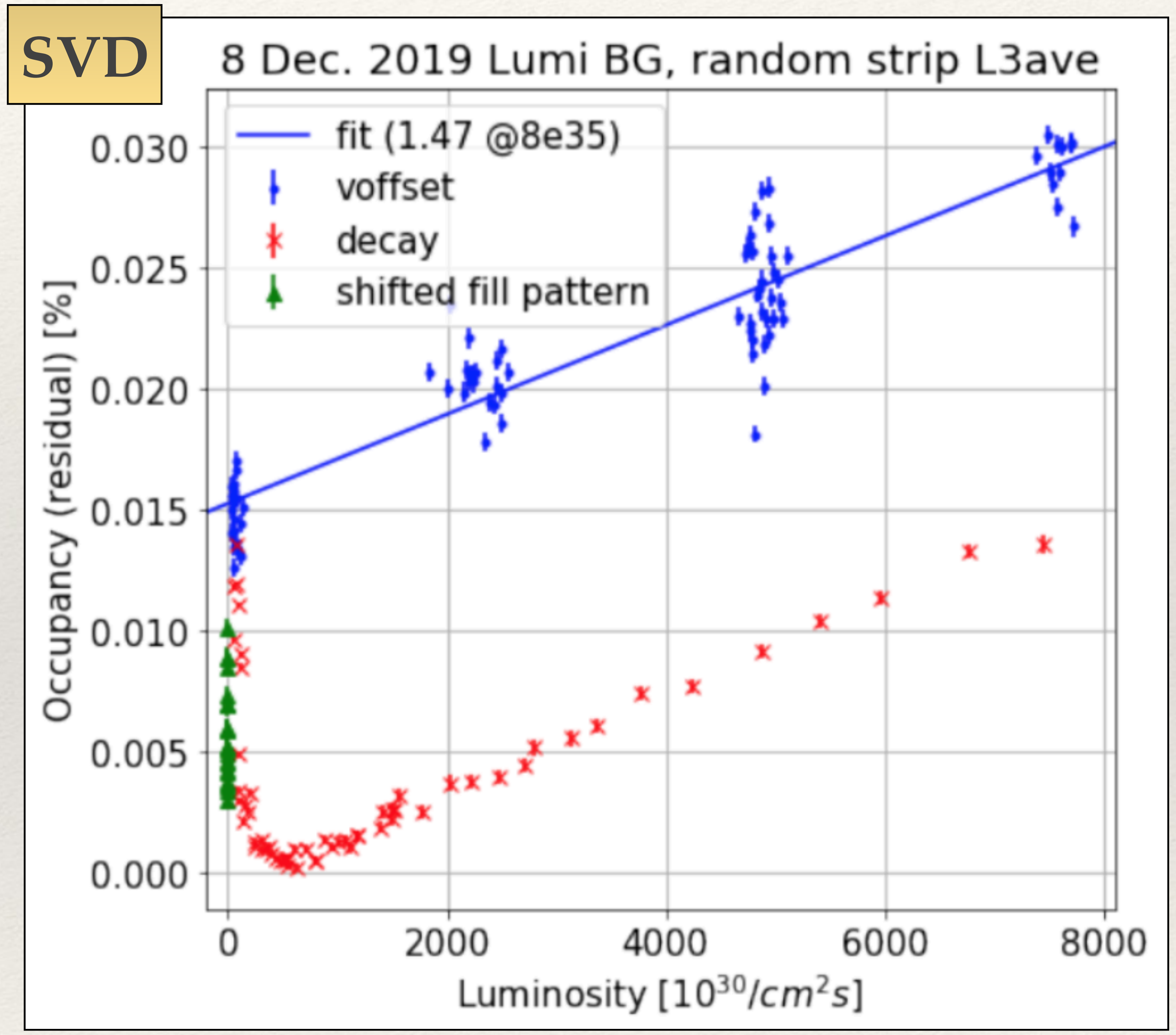


Luminosity background

- Luminosity background evaluated after single beam background subtraction
- Vary luminosity in three ways: vertical offset scan, n. of bunches, beams decay.
    - Different contributions depending on the data set, further studies in 2020 runs.
- Background composition: 80% LER, 10% HER, 10% Lumi BG, 60% LER beam-gas



Most of the hits due to comics and electronic noise, but still clear dependence on luminosity.

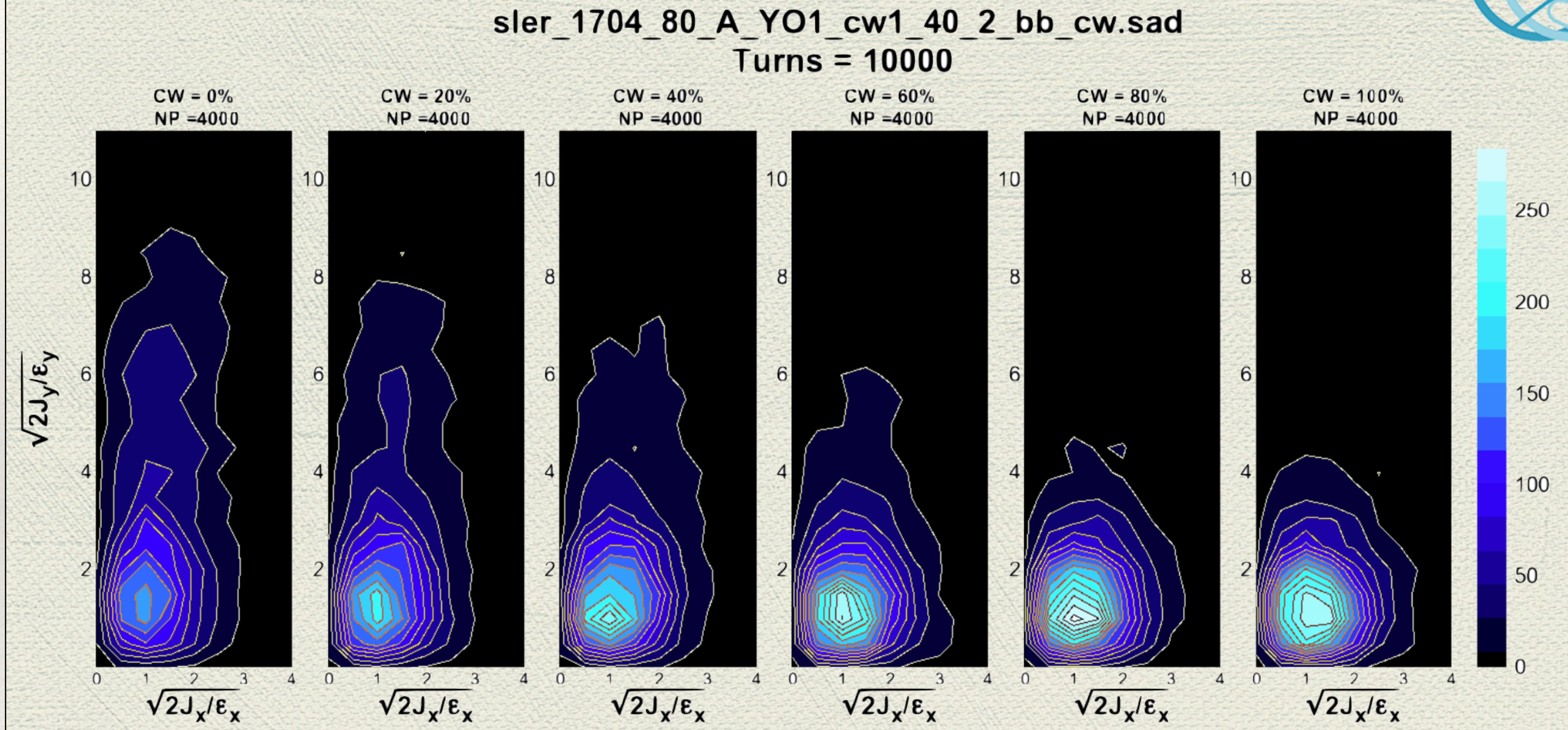


Clear dependence on luminosity.
Difference between vertical-offset and beam-decay scans.

Possible use of crab waist in 2020 run

Oide-san - SuperKEKB workshop - 30/01/2020

Beam distribution for various CW ratios ($\beta_y^* = 1$ mm)



- Same contours for all CW ratios.
- Suppression of the tail as well as higher density of the core are visible, even for CW = 20%.
- CW = 80% is the best for the luminosity, better than 100% (look at the density of the core).

- To be considered using crab waist:
  - Luminosity optimization
  - Touschek BG increase
  - Dynamic aperture decrease
- Optimal crab waist sextupoles strength around 60%.